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SMALL APPARATUS FOR MEDICAL X-RAY EXAMINATION

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A description is given of the connections and construction of two small portable X-ray apparatus for medial diagnosis, the "Centralix" and the "Practix". The low-power appliances are used in cases where the patient to be examined cannot be transported to the X-ray laboratory of the hospital, and also for cases where it is unnecessary to use high intensities of X-rays (photography of the teeth, etc.). In such small apparatus the X-ray tube and the high-voltage generator are constructed as a single unit. In the "Centralix" apparatus this has been done by giving the iron of the high-voltage transformer the shape of a hollow cylindrical ring, in the cavity of which the windings are placed and in the axial core the X-ray tube. This gives a very compact and light unit. In the case of the "Practix", for the sake of a better heat dissipation, a less compact structure has been chosen; a heat balance shows that this apparatus may very well be used for continuous routine work (fluoroscopy). The two appliances may be used either without special supports or in combination with different specially constructed standards, some of which are portable.

The visitor to the X-ray laboratory of a modern hospital will generally be impressed by the large and seemingly complicated apparatus which he finds there: large X-ray tubes, supported by heavy standards, large high-voltage generators, heavy cables, complicated arrangements for placing the patient and the film holder in position, etc. [1]). The fact that such large apparatus has been found necessary in the development of X-ray technology is due to the desire to be able to obtain the best possible X-ray pictures in all cases, even for parts of the body which are difficult to photograph, such as lungs, stomach, pelvis, etc. For these purposes high X-ray intensities and thus high-power apparatus are required.

Because of its size and weight this apparatus is more or less bound to a permanent position and it is necessary to bring the patient to the apparatus in question and to place him in a certain position in relation to the apparatus. Often enough, however, cases occur in which this is impossible. It is only necessary to consider patients with serious fractures, with fractures to be treated by extension, patients who are confined to bed in their homes, etc. In order, nevertheless, to be able to make an X-ray examination in such cases, the doctor will be willing to accept a lower standard of quality in the X-ray picture or of universal applicability of his X-ray apparatus, if he can have an apparatus which is portable and which offers the necessary freedom in setting it up.

On the other hand there are also cases where ease in moving and adjusting the apparatus — although always an advantage — is not strictly necessary, but where only such low X-ray intensities are needed that the use of a high-power apparatus would be extravagant. This is true for instance of the X-ray examination of the jaw and teeth by the dentist.

For these cases in which either willingly or unwillingly the doctor must accept a lower X-ray intensity, Philips have been one of the first manufacturers to develop portable X-ray apparatus of low power (the first was the "Metalix" Junior apparatus which appeared on the market in 1927). At present mainly two appliances of this type are being made, and they will be described in the following.

General construction of X-ray apparatus

It is clear that appliances of high power will be large and those of low power small. But for a better understanding it is useful to point out the reasons

[1]) See for example H. A. G. Hazeu and J. M. Ledeboer. A universal apparatus for X-ray diagnosis, Philips techn. Rev. 6, 12, 1941.

for this on the basis of a survey of an X-ray installation.

The X-ray tube which works with voltages up to 100 kV in medical diagnosis, must in the first place be large enough to ensure the required high-voltage insulation, in particular that between the anode and the cathode leads. The dimensions become greater when the tube is surrounded by an earthed jacket for the protection of doctor and patient, since the necessary insulation distances must be maintained between jacket and leads. Furthermore, when the tube is intended for continuous use (fluoroscopy) it must also have a sufficiently large surface to dissipate the heat developed on the anode without excessive rise in temperature.

The size and weight of the high-voltage generator are determined, besides by the above mentioned requirements of insulation and heat dissipation, to a large extent by the desire to keep the heat development low, for which purpose a heavy core and heavy windings of the high-voltage transformer are necessary. At the same time this heavy construction of the transformer is also desired in order to limit the voltage losses which occur [2]) when large tube currents are taken off (up to 700 mA in large installations). In general the A.C. voltage, after having been transformed upwards, is rectified, since by this means the yield of X-radiation per mm^2 surface of the focus can be considerably improved.

In order to be able to adjust the X-ray tube sufficiently easily it is connected to the poles of the fixed generator by means of two long flexible high-voltage cables. As to the further accessories such as standards, regulation arrangements for voltage, current, time of exposure, etc., they become proportionally larger and more complicated as higher and higher requirements are made of the performance and universal applicability of the installation.

If our requirements are lower, then in the first place a lower tube voltage and a smaller tube current can be used. If the voltage is limited to 60 of 65 kV instead of 100 kV — it is impossible to go much lower since the efficiency of the excitation of the X-rays and the penetration of the rays becomes too small — tube and generator become considerably smaller, since the insulation difficulties increase much more rapidly than the voltage. The tube current can for many purposes be limited to 10 or 5 mA [3]); the high-voltage generator then becomes much smaller and lighter, especially when we do not make too great demands as regards the specific focal loading, and therefore omit the high-voltage rectifier with the necessary valves and other appurtenances.

When the tube and the source of high voltage have been reduced in this way to more modest dimensions it is only necessary to consider the cable, because the other parts of the installation have meanwhile disappeared automatically or have shrunk in size appreciably. The support for the patient is automatically eliminated in the applications for which the apparatus is intended, the standard for the tube becomes smaller and lighter in proportion to the tube itself, and the arrangements for regulation also become much simpler when we confine ourselves to less difficult objects and thus make fewer or no requirements as to adjustability of the voltage, etc. The dimensions of the high-voltage cables, however, and of their leads through the earthed covering of the tube are mainly prescribed by the necessary insulation, and have thus participated only to a limited extent in the shrinkage of the generator. While the cable was originally introduced in order to be able to adjust the tube easily free of the generator, it is now found that, from a given power value on, the cable itself becomes heavier and offers more hindrance to manipulation than the generator! It is obvious that having reached this limit of power it is better to omit the cable and combine the high-voltage transformer and the tube to a single unit. The necessary electrical energy can be supplied to the "unit" thus obtained from the light mains by means of a thin low-voltage cord.

This fundamental principle is realized in two different ways in the small Philips apparatus. We shall first consider the simpler apparatus, the "Centralix".

The "Centralix" apparatus

The connections

In the construction of this apparatus especial attention was paid to its application in the dentist's

[2]) This is of special importance for the fine regulation of the tube voltage; see in this connection the article referred to in footnote [1]).

[3]) In fact the quality of the X-ray picture need not immediately depreciate very much upon decrease in the tube current. A smaller tube current makes it possible, with the same maximum specific focal loading, to use a smaller focus (with a smaller focus the specific focal loading even becomes slightly greater due to the lateral heat dissipation in the anode block). Because of this for the same geometrical lack of definition, the distance between focus and object can be reduced, thus obtaining a greater X-ray intensity on the film. When the object is thick, however, an increasing distortion of the X-ray picture results. With thin objects, such for example as the jaw and teeth, hands, etc. this distortion is of no importance.

practice. In this application the same tube voltage of about 58 kV can always be used. Since in jaw exposures the distance between focus and film can be made very small (15 to 20 cm, with a focus of 1.2 × 1.2 mm, see footnote [3])) a tube current of 5 mA is sufficient to be able to work with reasonable exposure times (several seconds maximum) in all cases occurring.

While in apparatus with adjustable voltage and current a separate heating current transformer is necessary in order to be able to vary the tube current (*i.e.* the cathode emission) independently of the tube voltage, in this case, where only one current-voltage combination occurs and the heating voltage thus has a fixed relation to the tube voltage, the filament can be supplied from a pair of extra windings on the high-voltage transformer. The connections thus become extremely simple, see *fig. 1.* The secondary winding of the high-voltage transformer is earthed at the middle, so that each pole need be insulated for only half of the voltage (about 30 kV). At the cathode pole the extra windings S_3 for the heating current are added, as well as a small resistance R_1 with which the heating current is set at the correct value upon assembly of the whole. The primary winding of the transformer is connected to the 220 V mains *via* a switch which is operated by means of a timing device. With this timing switch, which may be compared with the shutter of a camera, the exposure time is regulated.

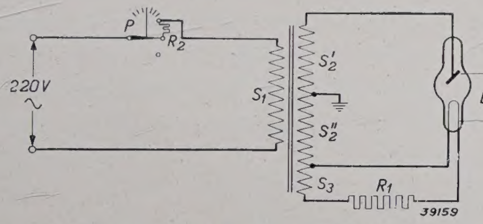

Fig. 1. Connections of the "Centralix" apparatus. B X-ray tube with anode A and hot cathode G; S_1 primary, $S_2' + S_2''$ secondary windings of the high-voltage transformer, S_3 extra windings for the filament current; R_1 regulation resistance for the heating current (regulated in the factory); P mains switch operated by a relay. Upon switching on, the resistance R_2 is first in series for several tenths of a second, and the voltage and current of the tube are slightly below normal, so that practically no X-radiation is excited, while the filament already nearly reaches the full required temperature.

The transformer

A nice solution has been found for the problem of combining the X-ray tube and the transformer. It is illustrated in *fig. 2.* Fig. 2*a* shows the simplest and most commonly used form of a transformer (so-called core transformer): the primary and secondary windings are wound around an iron core which is continued in the form of a yoke around the coils to give a closed magnetic circuit. The yoke can also be divided into two parts and the second half can pass around the other side of the

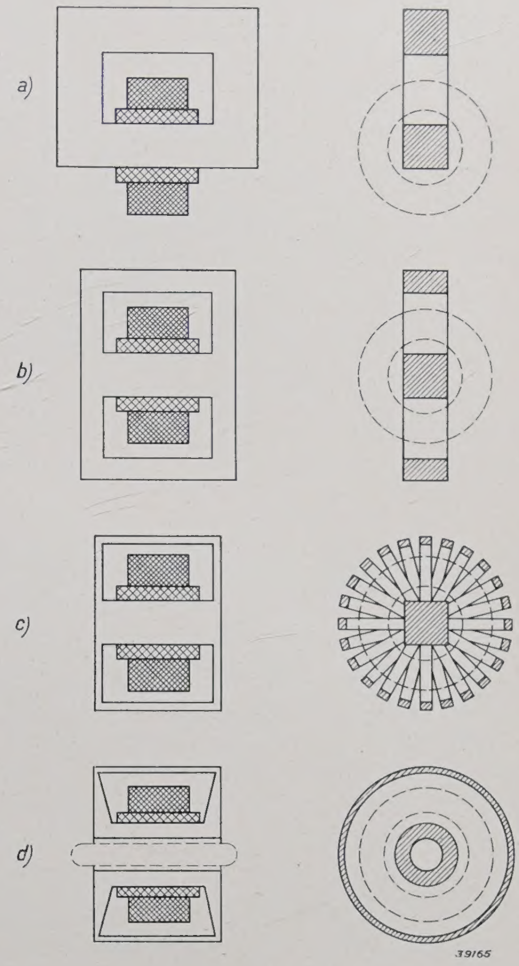

Fig. 2. By subdivision of the yoke of the ordinary core transformer (a) one arrives, *via* the shell transformer (b) at the cylindrical construction (c), from which by leaving a cylindrical opening at the axis the form of the "Centralix" apparatus is derived (d).

coils, see fig. 2*b* (shell transformer). In this case it is found that less iron is needed for a given induction. Still less iron is used when we go a step farther and divide the yoke into a large number of parts which surround the coils radially, see fig. 2*c*. In the "Centralix" apparatus this last method is actually followed, but with a space left free along the axis of the cylindrical structure formed. The X-ray tube is housed in this space, fig. 2*d*. In this way an extremely small and compact whole is obtained.

In *fig. 3* the construction of the transformer is given in somewhat more detail. The two halves of the secondary winding lie side by side as two separate coils around the cylindrical iron core, and the earthed extremities (*i.e.* the middle of the secondary winding) lie closest to the iron. In the

successive layers of the winding the voltage becomes higher and higher and the outermost layers finally carry the full voltage of about 30 kV with respect to earth, so that here the two coils for about 30 kV with respect to the iron and for

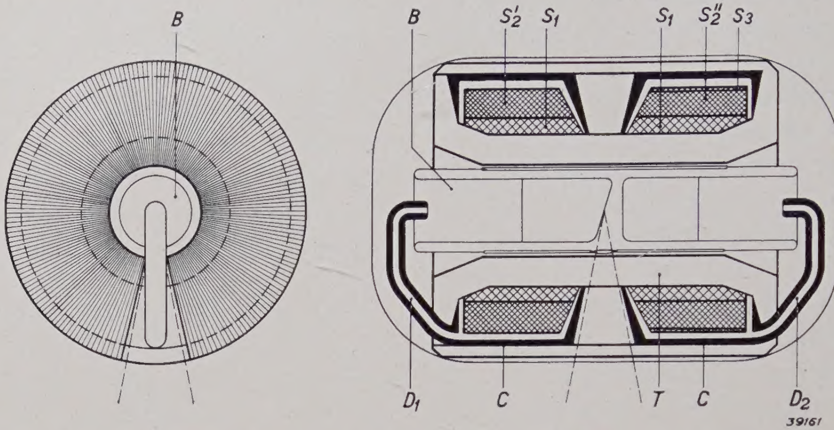

Fig. 3. Cross section of the "Centralix" apparatus. The X-ray tube B placed at the axis is drawn with fine lines. T transformer core in the form of a cylindrical hollow ring. S_1 low-voltage, S_2' and S_2'' high-voltage windings. C "Philite" cylinders, D_1 and D_2 anode and cathode leads.

about 60 kV with respect to each other must be insulated. For the insulation between the coils and the iron a relatively small distance was already enough, because of the fact that the side of the iron facing the coils forms a completely smooth cylindrical surface with no corners or edges which might cause local increases of the field strength. In order, however, to be able to reduce the distance still further and thus make the iron body still smaller for the same volume of coil, each coil was surrounded by a "Philite" cylinder (C in fig. 3), while the intermediate spaces were poured full of a solid insulating mass (compound). In order to obtain the necessary mutual insulation distance between the tops of the two coils, the coils are wound with a cross section which becomes narrower toward the outside (trapezium-shaped). As may be seen in fig. 3, a V-shaped opening thus automatically occurs in the longitudinal cross section, which is necessary in order to allow the passage of the effective beam of X-rays from the tube lying inside. The X-rays emitted in other directions are cut off by the transformer, so that no special lead jacket is necessary for protection against these rays. This is an extra advantage of the method of construction here chosen with the tube and transformer combined, as is also the fact that the focus of the tube now lies close to the centre of gravity of the whole unit: because of this the focus remains in the same spot when the apparatus is suspended on a standard and rotated and this makes the adjustment easier.

The iron core is built up of laminae on planes through the axis, so that the diagram in fig. 2c of an iron circuit divided in many independent yokes is actually realized. The laminae do not fill the whole circumference but leave a small sector open (fig. 3) through which the leads D_1 and D_2 for the connections of the high-voltage winding are laid to the X-ray tube. At the same time this leaves the necessary opening in the transverse cross section for the passage of the effective X-ray beam.

The X-ray tube

The tube itself is shown in cross section in *fig. 4*. It is of the usual construction of Philips tubes in which the space between cathode and anode (discharge space) is surrounded by an earthed metal cylinder. This cylinder is here made quite long, in order to ensure adequate protection of the glass

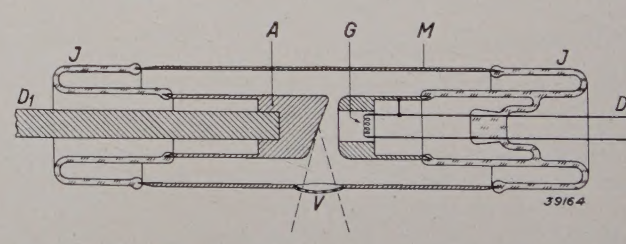

Fig. 4. Cross section of the X-ray tube of the "Centralix" apparatus. A anode, G filament surrounded by cathode cap, M earthed metal cylinder, V window for the X-rays, I bent glass insulation sections.

parts of the tube against secondary electrons. In order to obtain sufficiently long paths for creeping discharges between the metal cylinder and the electrodes without lengthening the tube, the glass sections of the tube which connect these parts mechanically and separate them electrically are bent as shown in fig. 4. In this way a very short

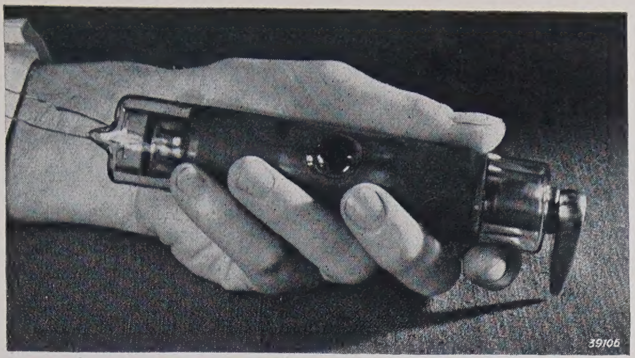

Fig. 5. X-ray tube of the "Centralix" apparatus, designed for a tube voltage up to about 60 kV and a tube current up to about 10 mA.

and sturdy tube is obtained, see *fig.* 5. Especial attention had to be paid to the insulation between the tube electrodes and the iron core of the transformer. In order to obtain at all points the necessary distances *via* glass and air between the earth potential plane (the iron core) and the leads at high voltage, the cylindrical opening of the transformer body has at both ends the funnel shape visible in fig. 3. Moreover, the leads are here again covered with compound.

A remarkable feature of the tube is the construction of the cathode. An ordinary X-ray tube works so far in the saturation region of the cathode emission that at 1/3 of the maximum working voltage the tube current already reaches its peak value, see *fig. 6a.* The result is that over a large part Δt of the period of the alternating current there is a considerable dissipation of energy, while because of the sharp increase in the efficiency of the excitation of the radiation with the voltage, it is only in the neighbourhood of the peak value of

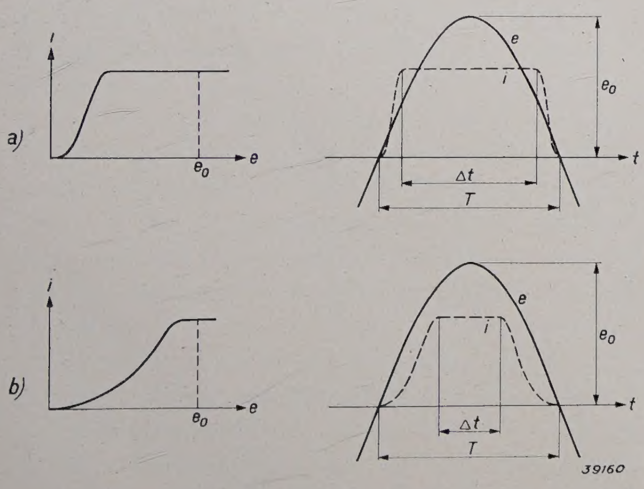

Fig. 6. *a*) Cathode emission (tube current) *i* as a function of the tube voltage *e* in a normal X-ray tube. The maximum tube voltage e_0 lies so far in the saturated region that the tube current has the saturation value over a large part Δt of the period *T* of the A.C. voltage supply.
b) Same as in (*a*) for the tube of the "Centralix" apparatus. The tube current now only reaches its saturation value when the A.C. voltage is near its peak value. The radiation yield is thus better than in (*a*).

the A.C. voltage that any appreciable X-radiation is obtained. By placing a cathode cap of a certain form (a kind of "grid") around the filament, the effect of the space charge which tends to retard the emission of the filament, can be so much increased that only close to the peak value of the tube voltage does the maximum tube current begin to flow, fig. 6*b*. The ratio between the total X-ray energy and the total anode load is hereby considerably improved. This device can of course only be employed when about the same tube voltage is always used, as is the case with the "Centralix" apparatus; in the case of an ordinary tube which works with very widely diverging tube voltages, it must still work in the saturation region of the emission at the lowest voltage used, so that a situation like that in fig. 6*a* is automatically excluded at the highest voltages.

Method of suspension and use of the apparatus

The tube and the transformer are surrounded by a smooth chromium-plated jacket, while the cylindrical body thus obtained, which can be rotated about its axis, is hung in a metal fork, see *fig.* 7.

Fig. 7. The "Centralix" apparatus together with relay switch mounted in a fork and provided with "Philite" cone for directing the X-ray beam.

On this fork is also the relay switch which can be set at exposure times between $^1/_4$ and 12 seconds, and which is operated with a continuous release such as is used in cameras. Over the opening through which the X-rays are emitted a "Philite" cone is screwed, by means of which it is possible to ascertain whether the central ray of the X-ray beam is directed upon the object. This device for the

directing of the beam is necessary because in this case, in contrast to the case of the ordinary large X-ray apparatus, there is no fixed relative orientation of film, object and focus. The elimination of this fixed orientation was the main object in the construction of the small apparatus. Instead of the cone a lead glass or metal tube can also be used, which at the same time limits the lateral spreading of the X-ray beam, or, with greater distances between focus and film, a telescopic centring rod. This latter must of course be removed during the exposure.

Since the apparatus (without fork) with a longest dimension of 25 cm weighs only 12 kg, it is often possible to improvise some kind of support for it when it must be carried about. For use by the dentist the apparatus can be hung on a movable standard or on a wall bracket which can be extended and turned in all directions. In photographing the jaw the film is placed in the patient's mouth and pressed against the teeth to be photographed. *Fig. 8* shows a photograph which was taken this way with the "Centralix" apparatus.

Fig. 8. X-ray photograph of teeth (back right of lower jaw), obtained with the "Centralix" apparatus. The extent and position of the metal fillings is very clearly visible.

The "Practix" apparatus

In making a compromise between required performance and permissible size of an X-ray installation, the emphasis may of course be laid as desired more on the one or on the other feature. In the case of the "Centralix" the emphasis was laid much more on obtaining a small and simple unit. Experience has, however, shown that there is also need for an apparatus where the emphasis is more in the other direction: *i.e.* an apparatus which may still be taken to the patient and adjusted, but which for the rest may be somewhat larger and more complicated in order to permit a correspondingly greater versatility. This involves not only the desirability of being able to make exposures with a somewhat larger and an adjustable current, but particularly that of being able to use the apparatus in fluoroscopy. The "Practix" apparatus meets these requirements.

The connections

This apparatus is designed for two voltages, namely one of about 60 kV which is used for photographs of the skull, shoulder, vertebrae, etc. and one of about 52 kV for photographs of the jaw, etc. [4]). The higher voltage is obtained very simply by introducing a tap on the primary winding, thus increasing the transformer ratio. In this case, however, the filament of the X-ray tube cannot be supplied directly from a winding on the high-voltage transformer, since at the lower voltage stage the filament voltage would then be 20 per cent lower and the cathode emission (the tube current) therefore about 90 per cent lower than at the higher voltage stage.

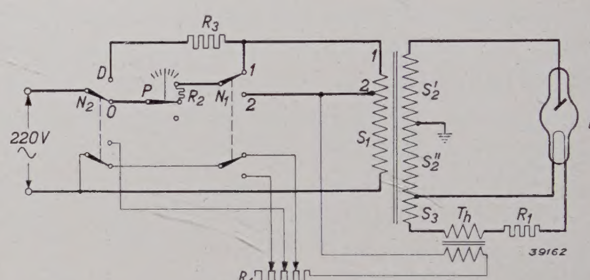

Fig. 9. Connections of the "Practix" apparatus with two voltage stages for photography. On the primary winding S_1 of the high-voltage transformer two taps *1* and *2* are introduced between which a selection is made with the switch N_1. The correct tap on the series resistance R_4 of the auxiliary transformer T_h for obtaining a tube current of 10 mA in each case is hereby also selected. With the switch N_2 one switches over to "fluoroscopy", whereby automatically a third tap on R_4 reduces the current to 3 mA. R_3 is a damping resistance, the remaining letters have the same significance as in fig. 1.

In order to avoid this, in adjustable apparatus, as was mentioned above, a separate heating current transformer is used. For the sake of saving weight and space in our case, however, a different method has been followed which is illustrated in the diagram of the connections, *fig. 9*. The filament voltage is supplied mainly by a winding S_3 on the high-voltage transformer. In series with this is a small auxiliary transformer T_h, whose primary winding is connected to the mains *via* a resistance R_4 with different taps. By connecting in series a large part of R_4 at the higher voltage, and a small part at the lower stage, the small transformer T_h supplements the filament voltage each time to exactly the desired value (tube current 10 mA). Since T_h only has the character of a correction

[4]) The lower voltage stage is omitted in the apparatus designed especially for dentists, since the higher stage is sufficient for photographs for ordinary diagnostic purposes. The commutation for fluoroscopy desribed further on, however, is retained.

element, it may have a very light construction (see below).

In fig. 9 it may be seen that the choice of low or high exposure voltage is made simply by moving the switch N_1. A second switch (N_2) serves for the transition from "photography" to "fluoroscopy". The high-voltage transformer is hereby connected to the tap (*1*) for low voltage (*via* a damping resistance R_3), while at the same time by a tap on R_4 the tube current is set at a smaller value than for photography, namely at 3 mA (since with this smaller tube current the voltage losses in the transformer, etc. also become smaller, the voltage is not about 52 kV in fluoroscopy, but about 57 kV). This decrease in tube current is possible since in fluoroscopy a lower X-ray intensity is sufficient and it is desirable since it would otherwise become much more difficult to limit the heating up of the apparatus to the necessary degree.

The construction

In order to keep the temperature of the apparatus sufficiently low in fluoroscopy, it is necessary to limit the losses in the transformer as much as possible, but at the same time to provide for a good heat dissipation from the transformer and the tube. This consideration made it necessary to give up the elegant construction principle of the "Centralix". In this case as far as the dissipation of heat is concerned, the situation is very unfavourable for the tube mounted inside the transformer as well as for the windings which are carefully insulated and shut up inside the hollow transformer, while at the same time the solid impregnating material, with which the windings as well as the ends of the tube are covered in order to limit the necessary insulation distances, may offer difficulties upon long continued heating; cavities may occur in the compound due to expansion and contraction, which cavities constitute a danger to the insulation [5]).

For these reasons the classical core transformer of fig. 2*a* was again used in the "Practix" apparatus, and oil was used as insulation material instead of compound. Thanks to the high breakdown stability (at higher temperatures also) of the oil the construction may again be made very small. While the filling with oil involves a greater weight of the apparatus and causes a structural complication in the necessity of an oil-tight seal, there is the advantage that the heat dissipation is greatly facilitated by the oil.

Fig. 10 shows a cross section of the whole apparatus. The X-ray tube, which is identical with that of the "Centralix" apparatus, is fastened against the free arm of the transformer core. A lead jacket around the tube provides the necessary protection against undesired rays. Beside the tube is the auxiliary heating current transformer (*Th* in fig. 9), which could be constructed with a simple straight core (thus with an open magnetic circuit) because of the low power required, around which, separated by an insulating tube are the low and high-voltage windings. The whole is immersed in oil and surrounded by an earthed jacket which is soldered in order to provide an oil-tight seal. The filling with oil (impregnation) takes place in a vacuum in order

[5]) In the "Centralix", which is used mainly for photography, the heating effect is so small that it presents no difficulties, mainly because of the fact that the compound is only used here in thin layers in which no appreciable cavities can be formed.

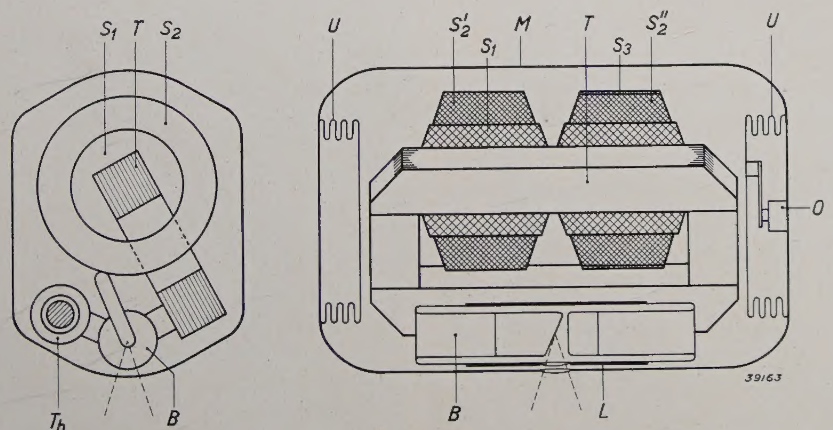

Fig. 10. Construction of the "Practix" apparatus. The high-voltage transformer has a core T of the ordinary form (square with almost square cross section) lying obliquely in the apparatus. On one arm of the core which lies about at the axis of the apparatus are the windings S_1, S_2' and S_2''; against the other arm the X-ray tube B surrounded by a lead jacket L is fastenend, and to this in turn the auxiliary heating current transformer T_h. The whole is immersed in oil and surrounded by the earthed mantle M. U are flexible cans to allow for the expansion of the oil, O switch for protection against overheating.

to avoid the presence of any residues of air and moisture which would be harmful to the insulation. Since with the temperature changes to be expected (—10° C in the winter, to +60° C after long continued fluoroscopy, for example) volume changes of about 5 per cent in the oil must be taken into account, accordion-shaped cans of very thin metal are attached to the side walls of the apparatus (fig. 10), which permit a motion of the bottoms of the cans of several millimetres and in this way the necessary expansion of the oil.

The heat balance of the apparatus

Due to the fact that the oil is set in motion by the heat during use, it may be assumed that the heat developed in tube and transformer will be distributed quite uniformly throughout the oil and thus over the whole apparatus. The power dissipated in fluoroscopy amounts to 166 watts (namely 131 watts in the tube and 35 watts in the high-voltage transformer and in the heating current circuit), while the surface of the apparatus is 1 600 cm². If we count on a heat dissipation of 10^{-3} W/cm² °C, which corresponds to that found in power oil-transformers, it will be seen that upon continuous use the temperature will rise until it is 166/1.6 = 104° above room temperature. Such a temperature increase could not of course be permitted; but actually it never reaches that point for two reasons: in fluoroscopy the tube is not actually in continual use, but there are occasional pauses, for instance for adjustment and for questioning the patient being examined and for calling the next patient. If the apparatus is switched off during these pauses which consume almost as much time as the fluoroscopy itself — and it is desirable to do so in order to expose the patient as little as possible to the X-rays — the watt consumption is reduced by one half, and the final temperature of the apparatus is limited to 20 + 104/2 = 72° C with a room temperature of 20° C. Moreover, it takes considerable time before this final temperature is reached, because of the heat capacity of the apparatus. The total heat capacity, *i.e.* for the oil and metal parts together, amounts to 2 400 cal. Beginning with the cold state (temperature T_0) the temperature of the apparatus T varies as follows:

$$T - T_0 = (T_{\max} - T_0) \cdot (1 - e^{-t/\Theta}),$$

where t is the time, $T_{\max} - T_0$ the above calculated final temperature increase (104 or 52°) and Θ is the quotient of heat capacity and heat dissipation per second and °C. From this it may be calculated that in the intermittent use referred to (ordinary fluoroscopy) and with the relatively high initial temperature of 25° C, a temperature of 60° C, which is permissible, is only reached after nearly 2 hours.

It is of course necessary when, as in this case, the gain in heat is greater than the heat dissipation, to introduce a safety device to prevent overheating of the apparatus during long continued use. This could very easily be done by means of the accordion-shaped cans on the side walls mentioned above, which are compressed when the oil is heated: on the movable bottom of one of these cans there is a lever which at a given displacement, corresponding

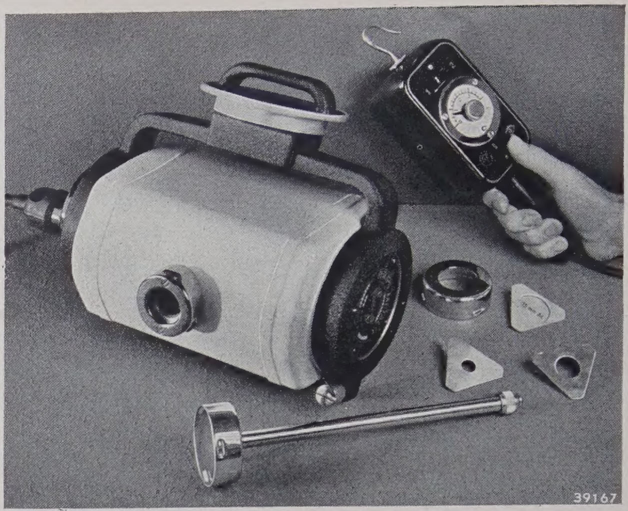

Fig. 11. The "Practix" apparatus mounted in a fork with "saucer" and handle. On the right the hand switch which contains the switches N_1 and N_2 for the two voltage stages and for fluoroscopy, as well as the timing switch and the resistance R_4. In the foreground a telescopically extensible rod which can be fastened to the window of the X-ray tube for directing the beam and several diaphragms and filters.

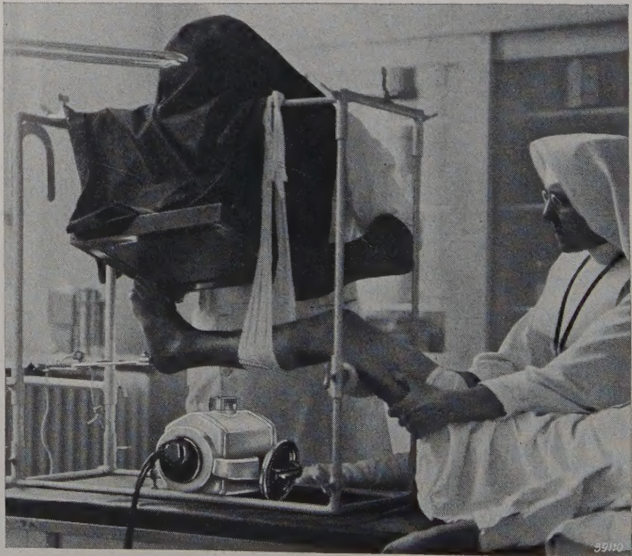

Fig. 12. Fluoroscopy with the "Practix" without the use of a standard (examination of leg fracture).-

to the highest permissible temperature operates a switch which interrupts the current supply to the high-voltage transformer. A temperature of 60° C is usually chosen as permissible limit.

The above calculation was found to be confirmed satisfactorily upon use of the apparatus in routine fluoroscopy examinations of the Medical Department of the Philips Plant. In this case for example in 1 hour and 40 minutes 70 persons were examined without the automat coming into action.

Method of support and use of the apparatus

The apparatus soldered into its housing is 30 cm long and weighs 14 kg. Like the "Centralix" it is mounted in a fork in such a way that it can rotate about its axis, see *fig. 11*. The relay switch which regulates the exposure time in the same way as in the "Centralix" is housed with the two switches N_1 and N_2 in a so-called hand switch. In this hand switch is also the regulation resistance R_4 (see fig. 9), with which, without opening the apparatus proper, the tube currents for photography and fluoroscopy can be further regulated if necessary.

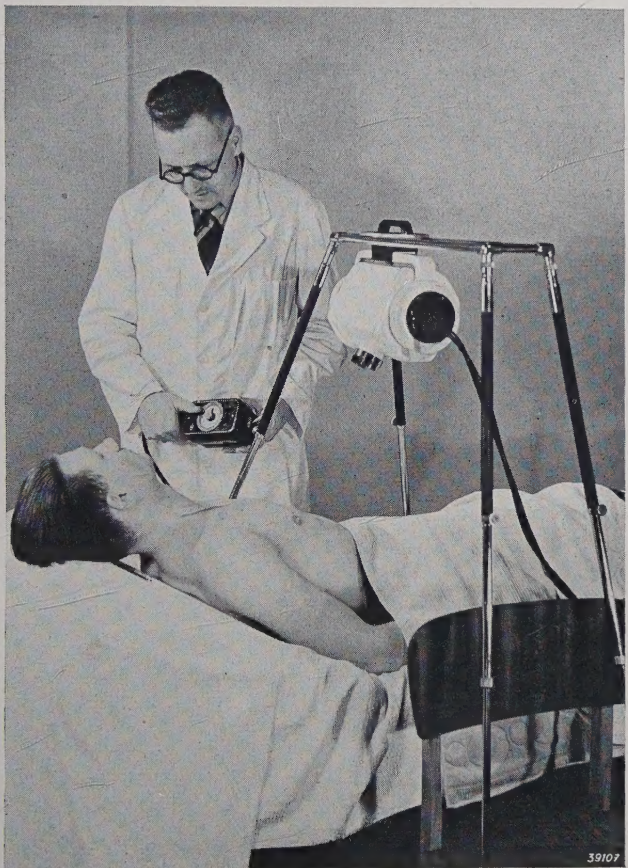

Fig. 13. Method of supporting the "Practix" with its saucer in the groove of a portable folding four-legged standard (lung photograph in patient's own home; lung photographs of satisfactory quality can be made with this apparatus).

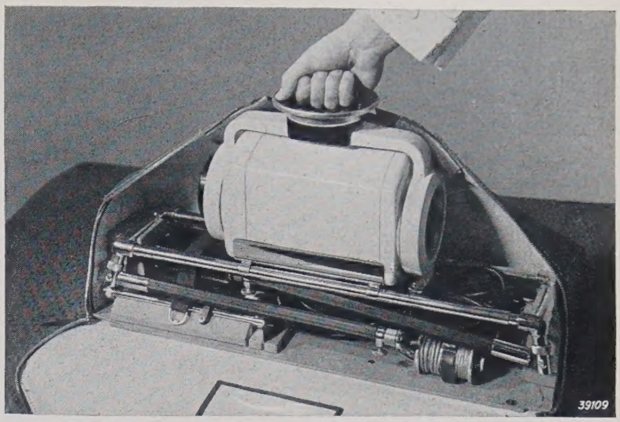

Fig. 14. The "Practix" apparatus, together with the folding four-legged standard and other accessories are housed in a small case.

Although it is also possible to take photographs with the "Practix" with improvised supports and also to use it for fluoroscopy in this way (*fig. 12*), for most cases it is nevertheless desirable to be able to fasten the apparatus to a standard. Great care was devoted to satisfying this desire without sacrificing the primary requirement of portability and adjustability in the case of a patient who cannot be moved. The simplest standard, which can easily be carried, is a folding four-legged one with extensible legs (*fig. 13*). By means of the ring with flange under the handle of the apparatus (so-called "saucer", see fig. 11) the apparatus can be hung between the two parellel horizontal tubes of the standard and can then be rotated not only about its own horizontal axis but also about a vertical axis. When folded, the standard with the apparatus and appurtenances can be housed in a

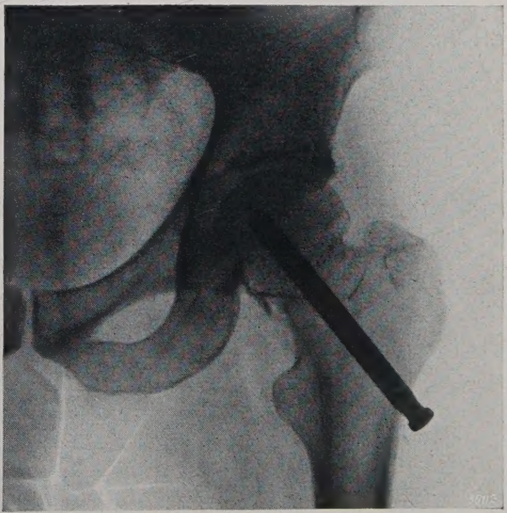

Fig. 15. Control photograph of a so-called nailing of the neck of the femur taken with the "Practix" apparatus during the operation. The photograph shows that a good picture can also be obtained of such a relatively difficult object.

small case (*fig. 14*); the total weight of this portable installation is only 25 kg, so that, for example, the general practitioner can easily take it with him in his car when he visits a patient in the country.

In addition a somewhat heavier and more convenient standard on wheels has also been developed, with which the apparatus can be fixed at any desired height between about 30 and 170 cm above the ground and at 20 to 60 cm distance from the column of the standard, while the X-ray beam can still be directed in any desired direction. Combined with this standard the "Practix" apparatus is particularly well suited for hospitals and field dressing stations. It has been in such use for a year with good results for the examination of wounded, the checking of the correct position of plaster casts and extensions, the control at the operating table of difficult surgical manipulations (*fig. 15*) and similar applications. It is the portability and ease in adjusting the apparatus which are here found to lead to a wider application of X-ray examination than would be possible if only large apparatus are used.

AN APPARATUS FOR THE INVESTIGATION OF SHARPNESS OF HEARING (AUDIOMETER)

by L. BLOK and H. J. KÖSTER. 534.771

Ear specialists are beginning to make more and more use of electrical apparatus which give continuous pure tones of variable intensity instead of the mechanical-acoustical devices which were formerly used in testing the hearing. Such an "audiometer", which has been developed from the tone generator GM 2 037 described previously, is here discussed. The method of employment in the determination of the sometimes very low thresholds of auditory sensitivity makes very strict requirements as to the freedom from interference of the signal of the audiometer. The measures are described by which these requirements can be satisfied. A discussion is also given of a number of auxiliary arrangements needed by the ear specialist in his examination. The results of the examination can be recorded in the form of an "audiogram" which gives the hearing loss in decibels as function of the frequency, and which may serve as one of the bases for the diagnosis and subsequent treatment.

The deviations in the sense of hearing observed in the case of persons who are partially deaf may exhibit great individual differences quantitatively as well as qualitatively. Quantitatively in the degree of depreciation of the sensitivity of the ear compared with that of a normal person, and qualitatively in the manner in which the deviation is manifested for the different pitches. Cases are known for example in which it is mainly the high tones which are heard poorly, and others in which the sensitivity is decreased only for the low tones.

The object of the ear specialist who desires to make an accurate diagnosis of a given case will in the first place be to measure the depreciation in the sharpness of hearing as a function of pitch. In addition he will attempt to determine the part of the ear in which the deviation is localized. The information obtained will not only furnish guidance for the therapeutic treatment to be applied, but will at the same time be important in deciding whether the patient should use some kind of hearing instrument and of what type this should be.

Until now the ear specialist has generally used a set of tuning forks to measure the decrease in ear sensitivity for different pitches. These tuning forks were struck in turn in a given way and allowed to vibrate freely. The patient then had to state for each tuning fork at what moment he no longer heard the sound. It is obvious that with a given initial intensity and a given damping (decrement) of the sound of the tuning fork, the patient will cease to hear the sound sooner, the lower his sensitivity for that pitch. The degree of depreciation of the ear sensitivity compared with that of a normal person was then indicated directly by the specialists by the "shortening" in seconds.

The objections to this very simple method are immediately obvious. The damping of a tuning fork depends very closely upon its frequency as well as upon all kinds of details of its construction. On the one hand, therefore, the results of different examiners using slightly different tuning forks may vary considerably. On the other hand the "shortening" found is not a good measure of the impor-

tance of the deviation. If, for example, two frequencies are considered for which the free vibration of the corresponding tuning forks is similar to that shown in *fig. 1a* and *b*, it is seen that a given depreciation in ear sensitivity (*i.e.* a given increase in the threshold value measured in decibels) gives quite different "shortenings" in the two cases [1]). Moreover, the sound intensity obtainable with tuning forks is often so small for low frequencies (fig. 1*a*) and the threshold value of the ear for these frequencies so high, that even with only relatively slightly deficient hearing the patient hears nothing at all from the very beginning, and thus no "shortening" can be measured at all, while with tuning forks for high frequencies (fig. 1*b*) the damping is often so great that it is difficult for the patient to indicate the exact moment at which for him the sound ceases, so that the measurement becomes very inexact.

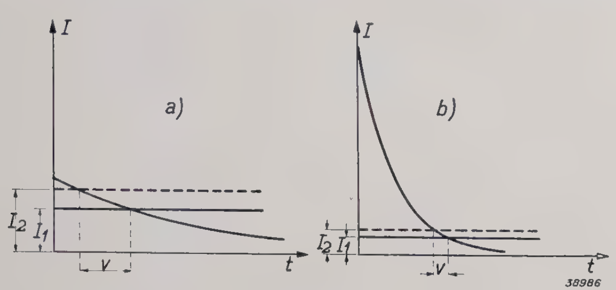

Fig. 1. Variations of the sound intensity upon the free vibration of a tuning fork of low frequency (a) and of high frequency (b). In both cases the normal threshold of hearing for the frequency in question (I_1) is represented by a full line, while the dotted line represents the raised threshold of hearing of a person with defective hearing (I_2). With a given ratio I_2/I_1, *i.e.* with a given loss of hearing in decibels, a quite different "shortening" v is found in the two cases.

These disadvantages have led to an attempt which has become more definite in recent years to replace the tuning forks and the other mechanical acoustical devices of the ear specialist by more modern apparatus which produces instead of damped tones continuous tones of variable intensity.

The obvious solution of this problem is to use the oscillators which are employed technically in the testing of parts of electro-acoustic installations, such as amplifiers, cables, loud speakers, etc. These oscillators give sinusoidal A.C. voltages with frequencies which can be varied over the whole acoustic range and with adjustable intensity. Such an apparatus, usually called a "tone generator", although for the original purposes it did not need to produce any "tone", has been described earlier in this periodical [2]). By connection to a loud speaker and several alterations in the construction. as well as by the addition of various auxiliary arrangements, an apparatus could be constructed from this tone generator which is especially adapted for the testing of hearing. The apparatus obtained (audiometer) and its use will be discussed briefly in the following.

Construction of the audiometer

Fig. 2 gives a very much simplified diagram of the original tone generator (type GM 2 307). For practical reasons [3]) the A.C. voltage of the desired low frequency is not generated directly by an oscillator, but is obtained as the beat between two higher frequencies f_1 and f_2. The two oscillators G_1 and G_2 generate voltages of these two high frequencies; the voltages are fed to the mixing valve M, in the anode current of which, therefore, all combination frequencies $mf_1 \pm nf_2$ occur. The signal with the desired low frequency $f_1 - f_2$ is filtered out by the filter F and raised to the necessary level in the amplifier V (normally 200 milliwatts). The output frequencies f_1 and f_2 of the oscillators G_1 and G_2 can be varied by means of rotating condensers between 100 and 101 or 100 and 85 Kc/s. By this means the differential frequency $f_1 - f_2$ obtained can be varied from 0 to 16 kc/s, *i.e.* within the whole acoustic frequency range. The regulation of the intensity is by means of the adjustable attenuator D.

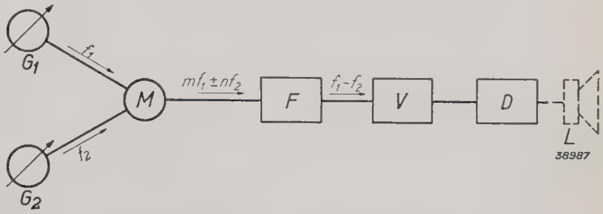

Fig. 2. Diagram showing the principle of the tone generator GM 2 307. G_1 and G_2 oscillators, M mixing valve, F filter, V amplifier, D attenuator. A loud speaker L may be connected behind D.

For testing the hearing a loud speaker is now connected behind the attenuator and the patient listens to the sound from the loud speaker. With the help of the attenuator the doctor can decrease the intensity of the sound to such a degree that the patient just barely hears it. If the attenuation factor is d_1 decibels in this case, a greater attenuation d_2

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[1]) The number of decibels hearing loss is also not an entirely true measure of the importance of the deviation when different frequency regions are compared. It is, however, a much more useful standard than the "shortening" and has, moreover, the advantage of being exact and reproducible.

[2]) L. Blok, A Tone Generator, Philips techn. Rev. 5, 263, 1940.

[3]) See the article referred to in footnote [2]).

will then be necessary for a normal person to reach the threshold of ear sensitivity in a similar way. The difference d_2—d_1 is the loss of hearing in decibels (depreciation in sensitivity of the ear) of the person with deficient hearing for the frequency in question.

It is clear that at least for the calibration of the audiometer it is also necessary to attenuate the tone produced by the instrument to the threshold of ear sensitivity for a normal person. Since this threshold is extremely low — at 1 000 c/s the normal ear perceives a sound intensity of 10^{-16} watts/cm^2 — much greater care must be taken in the case of the audiometer than in that of the ordinary applications of the tone generator that there are no disturbing sounds. The hum of the alternating current supply (the 50 c/s of the mains) must be considered as such, as well as the noise present in every amplifier, the hum of the output transformer, the overtones caused by non-linear distortion and finally the surges occurring when a tone is switched on.

The amplitude of the hum voltage in the tone generator amounted to from $^1/_2$ to 1 per cent of that of the effective signal. This means that the ear of the patient, in addition to the desired tone, would also always be exposed to a tone of 50 c/s with a 40 decibel lower intensity. If we consider the ear-sensitivity curve of a normal person, see *fig. 3*, it

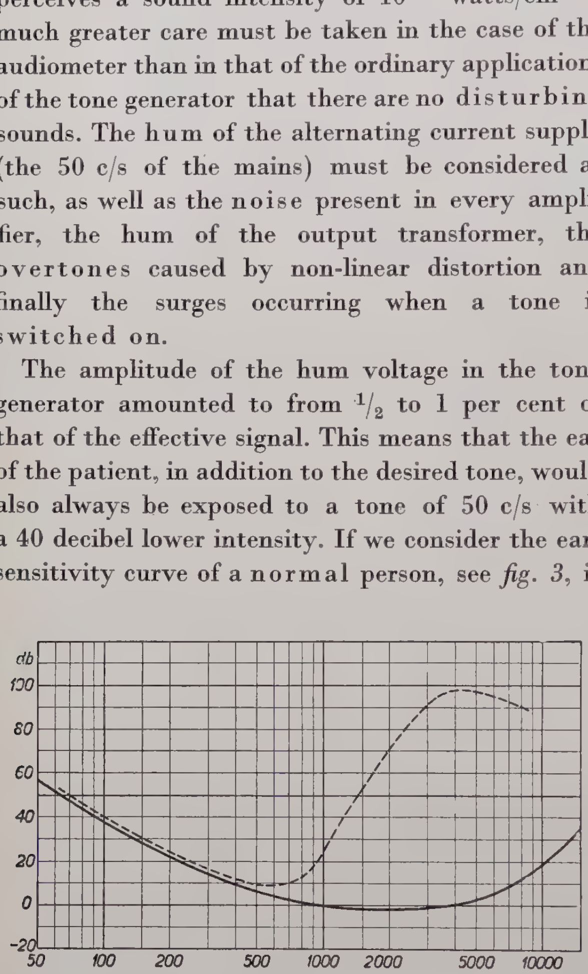


Fig. 3. Variation of the threshold value of sound intensity for a normal ear as a function of the frequency (full line curve, according to S. S. Stevens and H. Davis, Hearing, Wiley and Sons, New York 1938, p. 50). The threshold for a frequency of 1 000 c/s is arbitrarily set equal to 0 decibels. In a certain case of deficient hearing the broken-line curve may for example be found.

is clear that this cannot cause any error, since in the case of no frequency does the threshold lie 40 decibels higher than the threshold for 50 c/sec, on the contrary, it lies much lower for most frequencies. Let us now suppose, however, that a patient must be examined whose ear sensitivity is very much decreased only for high tones, for instance according to the broken line threshold curve in fig. 3. At a frequency of 4 000 c/s, for instance, this patient would not yet be able to hear the signal itself, but would, however, already be able to hear the 40 decibel weaker hum tone for 50 c/s, so that a false picture of the ear sensitivity would be obtained. In order to decrease the chance of such errors as much as possible special measures have been taken to make the hum of the apparatus still weaker. The plate voltage of the various amplifier valves is still more carefully smoothed than in the tone generator, and although the cathodes of the valves are of the indirectly heated type which of itself gives little cause for hum, the cathodes are nevertheless fed with direct current. The required D.C. voltage is furnished by a small selenium rectifier with a simple smoothing filter. In this way the hum is so limited that even with a loss of hearing of 105 dB at 1 000 c/s, which must be considered as total deafness, no errors can occur.

Similar considerations hold for the noise. The level of the noise, however, in the tone generator GM 2 307 is already so low that no special measures needed to be taken to combat it.

In the case of the hum of the output transformer of the amplifier V (see fig. 2), as a result of the mechanical forces of the magnetic field a part of the output is converted directly into acoustic energy, thus without passing through the attenuator and loud speaker. By keeping the patient sufficiently far away from the audiometer this source of interference could of course be eliminated immediately. In practice, however, the doctor who operates the audiometer and the patient will usually be seated at a distance of only a few metres from each other, and at a distance of 3 m for example the hum of the transformer was still observable in a quiet room. From the nature of the case the effect can only lead to errors when the signal of the loud speaker is very weak, *i.e.* when the attenuation factor is very large. This hum was therefore rendered harmless in the following simple manner. The attenuator, which permits a maximum attenuation of 155 dB — this is more than sufficient since with an attenuation of about 105 dB the lowest threshold which occurs is already reached —consists of a variable part with eleven steps of 5 dB each and two fixed parts each with an attenuation of 50 dB. The latter are only switched on when the eleven steps of the variable part have been traversed, thus when attenuations greater than 40 dB have been reached. Of these fixed attenuators, which are built up of a number of damping cells, a part with an attenuation of 25 dB is now, however, not connected behind, but in front of the amplifier V, see

fig. 4. The voltage on the input of the amplifier and therefore also that on the output transformer is thus now also attenuated by this factor. By this means the hum is made inobservable even with the highest attenuation factors.

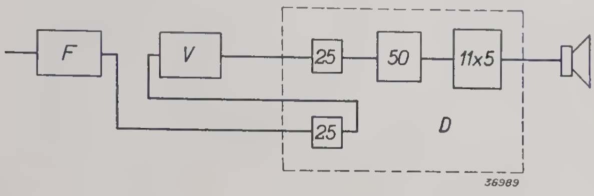


Fig. 4. The attenuator D consists of a part which can be regulated in 11 steps of 5 dB each and two fixed parts each of 50 dB which can be put into connection in turn. The first of these two 50 dB elements is split into two parts of 25 dB, one of which is connected in front instead of behind the amplifier V.

At the same time this measure is useful for combatting the errors due to overtones. These errors may occur especially with low frequencies, not only because the distortion of amplifiers is in general greatest here, but chiefly because of the characteristic shape of the normal ear sensitivity curve in this region. If for example it is desired to measure at a frequency of 50 c/s, the second harmonic of the signal (100 c/s) must according to fig. 3 be at least 18 dB weaker than the fundamental in order that the normal ear shall not hear the second harmonic rather than the fundamental tone. With deviating ear sensitivity curves still steeper slopes (*i.e.* still greater threshold differences within an octave) may occur, so that still higher requirements are then made of the freedom from distortion. In the case of the tone generator GM 2 307 the distortion amounts to an average of $^1/_2$ per cent with the maximum output (at low frequencies the maximum is 1 per cent), so that threshold differences of 40 dB in an octave can still be measured satisfactorily. With not too much decreased ear sensitivity, however, the performance of the audiometer is still considerably better, since then, in the manner described, an attenuating element of 25d B is connected in front of the amplifier, so that it has a much weaker signal to deal with and therefore much less non-linear distortion occurs.

The connection of a part of the attenuator in front of the amplifier is, however, a disadvantage for the level of noise. The noise is to a large extent generated by the first amplifier stage and will be of less importance relatively, the stronger the input signal of the amplifier. It was for this reason that the whole attenuator was not placed in front of the amplifier, which would of itself have been simpler and better for the desired combatting of the transformer hum and the distortion. In this way the noise is limited to such a low level that it can only become audible at a sound intensity of 70 dB above the threshold at 1 000 c/s.

Finally there remain the switching surges. When the loud speaker is switched on in the ordinary way there is always a click which may be considerably louder than the tone to which the patient must listen. This must be avoided. For this purpose the simple connections of the oscillator G_1 (fig. 2) shown in *fig. 5* are employed. As long as no tone is desired the switch S is closed and the condenser C is charged to a voltage of 20 volts. On the control grid of the oscillator valve therefore there is a negative D.C. voltage of 20 volts, the valve is over-biased and cannot oscillate. In order to switch on the tone the switch S is now opened. The condenser is slowly discharged *via* the large resistance R, the grid bias of the valve becomes gradually less negative and the valve begins to oscillate with an amplitude which grows slowly to the final value. Upon switching on the tone therefore no click occurs and the sound gradually (within 1 sec for instance) takes on the previously chosen intensity.

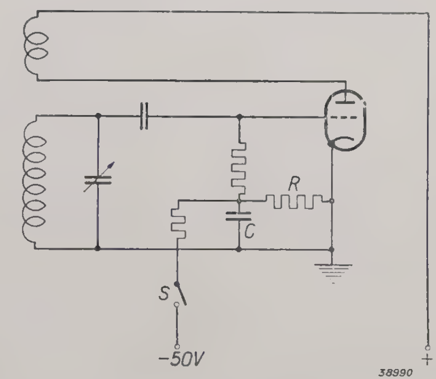


Fig. 5. Connections of the oscillator G_1 with RC circuit for the gradual raising of the oscillations to their final amplitude (avoidance of clicking sounds in the loud speaker). With the switch S closed the condenser C is charged to a voltage of 20 volts.

The complete arrangement

Fig. 6 is a photograph of the audiometer with several auxiliary instruments which are used in the examination. On the audiometer itself may be seen the dials of the two rotating condensers with which the desired pitch is obtained. The frequency of the tone produced is given simply by the sum of of the frequencies read off on the two dials. Above may be seen the knobs of the attenuator, a measuring instrument for insuring that the signal voltage without attenuation has the normal initial value, and below various switches and lamps for signaling purposes.

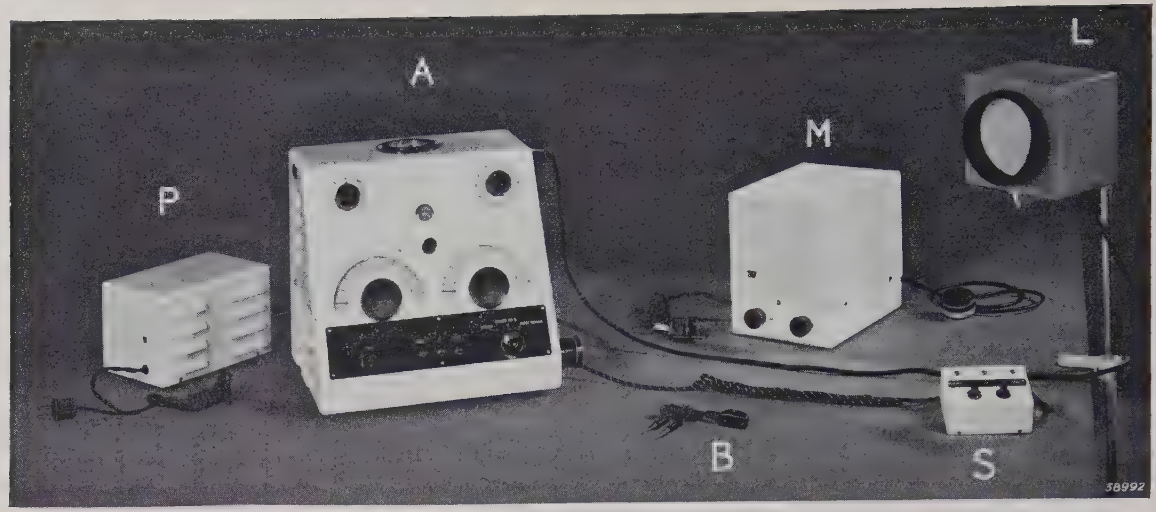


Fig. 6. Complete arrangement for the testing of the ear. *A* audiometer with frequency scales, attenuator knobs, etc. *P* necessary supply apparatus. *L* loud speaker, *S* box which is used by the patient for signalling. The loud speaker may if desired be replaced by the bone conduction telephone *B*. *M* auxiliary apparatus for so-called masking.

For the examination to take place smoothly the necessary communication between doctor and patient is by means of light signals. Both doctor and patient have three lamps in front of them, yellow, green and red (those of the patient are on the small box below the loud speaker in fig. 6). When the doctor switches on the tone the yellow lamp lights up in both cases. The patient must now press one of two buttons according to whether he hears the sound or not. If he presses the button "yes" the green lamps light, if the button "no" the red lights. In this way the threshold of hearing is very quickly and rapidly determined. By means of a switch the doctor can also make the tone continuous and then by variation of the frequency he can quickly determine the limits of hearing as far as pitch is concerned. Finally the doctor also has at his disposal a "simulator's switch". With this switch the tone generator is put out of action, while the signal arrangement continues to function. Then upon the lighting of the yellow lamp the patient should always answer "no", if he answers "yes" he is evidebtly desirous of making his hearing appear better than it is. Fatigue of the patient which no longer allows him to distinguish with confidence whether he hears the sound or not can also be detected by the doctor in this way.

A very small type of loud speaker has been chosen. This is desirable since the two ears of the patient must be examined separately, and with a large loud speaker it is difficult to restrict the influence of the second ear sufficiently. With the small loud speaker used this is provided for by a cylinder of felt against which the patient presses his head. The shielding of the free ear would be still better with the use of a head phone. This has not been employed, however, because in the first place resonance may occur in the relatively small column of air between membrane and ear drum which would cause the delusion of an increased sensitivity for some frequencies; and in the second place because the housing of the telephone pressed against the external ear also vibrates to a certain extent and may therefore stimulate an impression of sound through the bony structure.

This leads us to another important point in the ear examination: the localization of the defect. A depreciation in the sensitivity of the ear may be caused by defects in the inner ear (labyrinth) or by defects in the external and middle ear which conducts the sound to the inner ear (meatus, ear drum, bones of the ear). In the first case, which may for instance occur as a result of some disease or other, like scarlet fever, one speaks of perception deafness, in the second case of conduction deafness. The method of distinguishing between the two cases is by the bone conduction just mentioned: if the middle ear is defective the patient will still be able to obtain a satisfactory sound impression *via* the bone conductors; of the defect is in the inner ear the bone conduction will be of as little use as the air conduction *via* the ear drum. For this examination a bone conduction telephone (see fig. 6) has been provided with the audiometer. This is essentially an ordinary telephone, but one which is so constructed that the moving membrane makes only small deviations but can thereby exert high pressures. The membrane (actually the membrane is formed by the whole housing of the telephone) is pressed against the skull behind the ear. The

ear-sensitivity curve of a normal person has of course a different form for bone conduction than the curve of fig. 3. We shall not, however, go into that here.

The necessity already mentioned of only allowing sound to reach the ear which is being tested presents another problem to the examiner when he encounters a case of so-called unilateral deafness, in which one ear functions normally or approximately so. If in this case the defective ear has a considerable hearing loss, so that high sound intensities are necessary to reach the threshold of hearing, it is often unavoidable that the normal ear already observes a sound *via* air conduction around the head or *via* bone conduction through the head, while the defective ear still hears nothing. In order to eliminate this disturbing effect, or at least to remove its effect on the results of the measurement the normal ear is "masked". The normal ear is exposed to a "noise" of such an intensity that the ear takes on a sort of artificial deafness for the tone to be observed, while the perception of the defective ear is practically unafffected. As masking noise a tone may be used which is very rich in overtones and thus has a very sharp sound. The fundamental is best chosen in the same frequency region as the pure tone to which the defective ear is exposed. A small auxiliary apparatus has been constructed for obtaining the masking; it is shown in fig. 6 to the right of the audiometer. It is essentially a small tone generator giving a very distorted signal which can be set by means of a switch on five different fundamental frequencies appropriately distributed over the whole acoustic range.

Instead of the examination with pure tones it may sometimes also be desirable to carry out direct intelligibility tests, *i.e.* to discover the intensity level at which ordinary speech is understood by the patient. For this purpose the audiometer is provided with a connection for a gramophone pick-up, with which speech recorded on gramophone plates can be supplied to the amplifier input.

In conclusion a few words must be said about the working out of the results obtained. They can conveniently be recorded in an "audiogram", like that shown in *fig. 7*. The loss of hearing in decibels, *i.e.* the increase in the threshold value compared with that of a normal person, is here plotted as a function of the frequency, and the measured points are the successive octaves of the note C (64 c/s) according to the custom of ear specialists. The example reproduced is a typical case of unilateral deafness. The left ear is practically normal (broken line curve); for the right ear the full line curve is measured without masking, but the maximum in the neighbourhood of 1 000 c/s, which corresponds to a small maximum in the broken line curve. immediately suggests that in this threshold curve the normal ear also collaborated. With masking the much lower dot-dash curve was indeed found, which indicates a practically total deafness of the right ear.

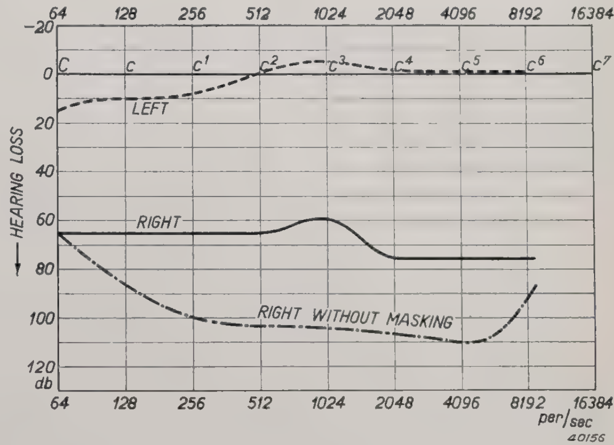


Fig. 7. Example of an audiogram. The hearing loss in dB is plotted directly as a function of the frequency. This was a typical case of unilateral deafness.

The audiogram now forms one of the bases of the diagnosis to be made and serves at the same time as documentation for later control of whether the defect has developed further and in what direction this has taken place. Finally the audiogram also furnishes the instrumentmaker with the necessary data when the ear specialist wishes to prescribe the use of a sound amplifier with an especially adapted frequency characteristic [4]).

[4]) See for example K. de Boer and R. Vermeulen, On improving of defective hearing, Philips techn. Rev., **4**, 316, 1939.

LECHER SYSTEMS

by C. G. A. von LINDERN and G. de VRIES. 538.566.5

The behaviour of Lecher systems with respect to travelling and stationary waves is discussed. The way is discussed in which Lecher systems can be employed as supply connections in transmitters, as high impedances in electrical circuits, as stabling resonators for high frequencies, etc.

Two electrical conductors which are strung parallel to each other, or which in certain cases are concentric, together form a Lecher system. In the last decade of the previous century many experiments had already been performed with such systems and J. J. Thomson, among others, pointed out their great significance in the excitation and propagation of electromagnetic waves. They were later used on a large scale in radio technology. As was already mentioned in an article in the previous number of the periodical [1]), the behaviour of such Lecher systems can be described to an certain extent by means of quasi-stationary concepts, although they are not fundamentally quasi-stationary systems. We shall go into this in somewhat more detail.

If we apply to the input of a Lecher system (left in *fig. 1*) a voltage V_1 of such a high frequency

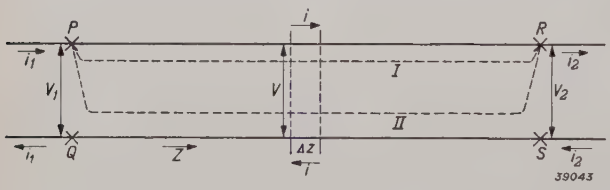


Fig. 1. Lecher system with input PQ and output RS, to which the voltages V_1 and V_2, respectively, are applied, and in which the currents i_1 and i_2, respectively, flow.

that the wave length is still large compared with the distance between the wires but not large compared with the length of the Lecher system, the currents will indeed be equal and opposite in every vertical cross section of the two conductors, but in the direction of length of the conductors the current i changes from point to point, as indeed does the voltage V between the two conductors. The change in current occurring along the conductors is a result of the displacement currents which flow through the capacity which exists between two conductors. Since the conductors have the same thickness at all points and are everywhere the same distance apart, it is possible to ascribe to a Lecher system a capacity C^I per unit of length.

In addition to this capacity C^I per cm, a Lecher system also has a self-induction L^I per cm; this is by definition the magnetic flux enclosed per cm length of the Lecher system at a current of 1 ampere. It is then found possible with the help of this self-induction L^I and capacity C^I uniformly distributed along the conductor to describe the behaviour of a Lecher system satisfactorily, and actually to apply to it the equivalent circuit of *fig. 2.* Even though the length of the Lecher

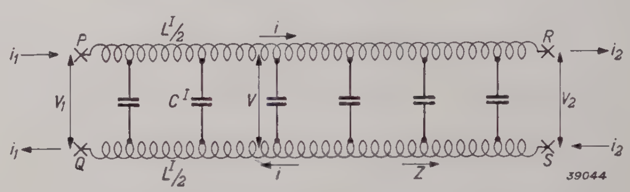


Fig. 2. Equivalent circuit for the Lecher system of fig. 1, which has a self-induction L^I per cm and a capacity C^I per cm.

wires is not small compared with the wave lengths, the Lecher system can, nevertheless, be treated in its transverse dimensions as quasi-stationary, and we shall call such a case semi-quasi-stationary. In our semi-quasi-stationary theory the difference in voltage between the points P and R or Q and S in fig. 1 may then not occur, since they are not defined [2]), but this is no disadvantage since it is only the differences in voltage between P and Q or R and S which are important in the theory.

Travelling waves

It is a well known phenomenon that waves travelling along a Lecher system can be propagated with a very definite velocity, and we shall now in the first place treat this phenomenon in a simple way [3]). For this purpose we consider a charge e (positive on one wire, negative on the other) distributed evenly over a length l of the Lecher wires, which causes a voltage V between the two

[1]) Resonance circuits for very high frequencies, Philips techn. Rev. **6**, 217, 1941.

[2]) It makes a considerable difference with regard to the necessary energy whether in fig. 1 a unit charge is moved from P to R along curve I or along curve II.

[3]) *Cf.* H. G. Möller, Grundlagen und mathematische Hilfsmittel der Hochfrequenztechnik (Springer, Berlin 1940) p. 172. See also O. Heaviside, Electromagnetic theory, Vol. III, p. 3 (1893, republished in 1922, Benn Brothers, London).

wires (*fig.* 3). The following then holds:

$$e = C^I l V. \quad \ldots \ldots \quad (1)$$

If these two charges which are originally distributed between $x = 0$ and $x = l$ move with linear velocity v towards the left, the current is :

$$i = C^I \, V v \quad \ldots \ldots \quad (2)$$

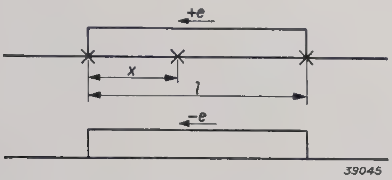


Fig. 3. A charge $+e$ is uniformly distributed over a length l of one of the Lecher wires; on the other wire in the same way is the charge $-e$.

The magnetic flux Φ between 0 and l at first amounts of $\Phi = l L^I i$ and decreases with time as the charge in its movement toward the left moves out of the region between $x = 0$ and $x = l$. The variation of Φ with the time is given by

$$\Phi = (l - vt) \, L^I i = (l - vt) \, L^I C^I V v \quad \ldots \quad (3)$$

The voltage between the two conductors at the point x is according to the law of induction equal to the decrease in Φ per unit of time:

$$V = -\frac{\mathrm{d}\Phi}{\mathrm{d}t} = L^I \, C^I \, V v^2 \quad \ldots \quad (4)$$

From (4) the square of the velocity is obtained:

$$v^2 = \frac{1}{L^I C^I} \quad \ldots \ldots \quad (5)$$

Any given distribution of charge will also be propagated at this velocity since such a distribution can always be built up of different charge distributions according to fig. 3. This simple result also follows directly from the electromagnetic vibration equations, which we shall now set up for a short section Δz of a Lecher system, which we may consider as a current circuit with self-induction $L^I \Delta z$ and capacity $C^I \Delta z$, while we neglect the ohmic resistance. The increase Δi of the current over a length Δz of the Lecher system is then given by

$$\Delta i = -\frac{\mathrm{d}}{\mathrm{d}t} \, (V \cdot C^I) \, \Delta z,$$

so that we obtain the following partial differential equation:

$$\frac{\partial i}{\partial z} = -C^I \frac{\partial V}{\partial t} \quad \ldots \ldots \quad (6)$$

According to (3) and (4) the voltage difference ΔV excited over a length Δz of the conductors is in the same way equal to

$$\Delta V = -\frac{\mathrm{d}}{\mathrm{d}t} \, (i \cdot L^I) \Delta z,$$

which gives us the partial differential equation

$$\frac{\partial V}{\partial z} = -L^I \frac{\partial i}{\partial t} \quad \ldots \ldots \quad (7)$$

By partial differentiation of these two electromagnetic equations (6) and (7) with respect to z and t we find the same equation for V and i:

$$\left.\begin{aligned} \frac{\partial^2 V}{\partial z^2} &= + L^I C^I \frac{\partial^2 V}{\partial t^2} \\ \frac{\partial^2 i}{\partial z^2} &= + L^I C^I \frac{\partial^2 i}{\partial t^2} \end{aligned}\right\} \quad \ldots \quad (8)$$

These formulae are analogous to the familiar equations for mechanical waves which are propagated along a stretched string, where instead of V or i we are concerned with the displacement of a point on the string, while instead of L^I and C^I the mass per unit of length and the reactionary force occur. Every twice differentiable function of $t \pm z\sqrt{L^I C^I}$, the so-called d'Alembert solution, satisfies equation (8). This means that every disturbance of the equilibrium which acts on the system at a given moment furnishes a solution to the equation if it is propagated unaltered in the negative or positive z direction with a velocity $v = 1/\sqrt{L^I C^I}$, as was the case with our rectangular charge distribution at the beginning of this section.

If we now take for the voltage a wave moving to the right with the velocity $1/\sqrt{L^I C^I}$:

$$V = f\,(t - z\sqrt{L^I C^I}), \quad \ldots \ldots \quad (9)$$

then with the help of (6) and (7) we calculate for the current

$$i = +\sqrt{\frac{L^I}{C^I}} \, f\,(t - z\sqrt{L^I C^I}) \quad \ldots \quad (10)$$

This is thus exactly the same form as for V, while the phases of i and V also correspond exactly at any point along the Lecher system. The quotient of the momentary values of voltage and current is constant, and the following is valid at every point along the Lecher system:

$$\frac{V}{i} = \sqrt{\frac{L^I}{C^I}} = \zeta. \quad \ldots \ldots \quad (11)$$

ζ is called the wave resistance of the Lecher system.

This behaviour of the Lecher system is quite analogous to what occurs in an aerial which is emitting electro-magnetic waves. The energy which is thereby radiated is manifested as an apparent resistance of the aerial, the so-called radiation resistance. The wave resistance ζ of a Lecher system may very well be considered as a one-dimensional radiation resistance.

If we have a Lecher system of finite length and connect the two wires at the right end by a pure resistance ζ, the Lecher system behaves as if it extended to infinity on the right. The relation between V and i at the position of the terminating resistance is exactly as in a wave moving to the right on an infinitely long Lecher system. If, however, the terminating resistances have a value differing from ζ there is a different relation between V and i. This deviating relation is not realized by a wave moving toward the right, but only by the superposition of a wave moving toward the right and a wave moving toward the left, which means that reflection takes place.

Velocity of propagation and wave resistance

For several cases of practical importance we shall specify more exactly the self-induction L^I and the capacity C^I per unit of length, in order to calculate from them the velocity of propagation and wave resistance of this Lecher system. In the first place we consider two metal strips with a width b and a distance apart d, lying parallel to each other (*fig. 4*). If d is made small compared with b the

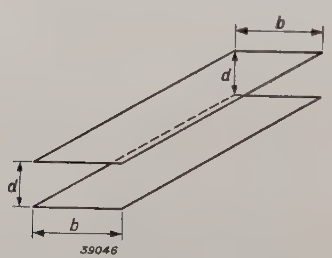


Fig. 4. Lecher system of wide strips. The distance between the strips is d and their width b.

capacity per unit of length in the z direction becomes

$$C^I = \frac{\varepsilon b}{4\pi d}\ \text{cm/cm} = \frac{\varepsilon b}{4\pi d}\,\frac{1}{9\cdot 10^{11}}\ \text{farads/cm}, \quad (12)$$

where ε represents the dielectric constant.

The self-induction L^I per unit of length for this simple case is also easy to find with the usual simplifications. If we assume the magnetic field H between the two strips to be homogeneous, and outside of them equal to zero, then

$$Hb = 0{\cdot}4\pi i\ \text{gauss cm.} \quad . \ . \ . \quad (13)$$

If μ is the permeability, the number of magnetic lines of induction which run between the two wide strips per cm in the z direction is $Bd = \mu Hd \times 10^{-8}$, and this by definition is the current i times the self induction L^I per unit of length:

$$iL^I = \mu Hd \cdot 10^{-8}\ \text{amperes henrys} \quad . \ . \quad (14)$$

From (13) and (14) it therefore follows that the self induction in henrys/cm becomes

$$L^I = \frac{4\pi\mu d}{b}\,10^{-9}\ \text{henrys/cm} \quad . \ . \ . \quad (15)$$

The velocity of propagation v for electromagnetic equilibrium disturbances in a Lecher system is according to (12) and (15)

$$v = 1/\sqrt{L^I C^I} = \sqrt{\frac{9\cdot 10^{20}}{\varepsilon\mu}} = \frac{3\cdot 10^{10}}{\sqrt{\varepsilon\mu}}\ \text{cm/sec.}$$

For a medium with a dielectric constant $\varepsilon = 1$ and 1 and a permeability $\mu = 1$ this becomes equal to the velocity of light of 3×10^{10} cm/sec which is universally valid for parallel conductors of any given cross section.

According to formulae (11), (12) and (15) the wave resistance becomes

$$\zeta = \sqrt{\frac{4\pi\mu d}{b}\cdot\frac{4\pi d}{\varepsilon b}\cdot 9\cdot 10^2} = 120\pi\,\frac{d}{b}\sqrt{\frac{\mu}{\varepsilon}}\ \text{ohms.}$$

If in an analogous way the capacity and self-induction per unit length are calculated for two concentric conductors with radii R_1 and R_2 (*fig. 5*) one finds

$$C^I = \frac{\varepsilon}{2\ln R_2/R_1}\cdot\frac{1}{9\cdot 10^{11}}\ \text{farads/cm,}$$

$$L^I = 2\mu\ln R_2/R_1\cdot 10^{-9}\ \text{henrys/cm.}$$

The velocity of propagation $v = 1/\sqrt{L^I C^I}$ now becomes $3\times 10^{10}/\sqrt{\varepsilon\mu}$ cm/sec here also, while for the wave resistance the following is obtained:

$$\zeta = \sqrt{2\mu\ln R_2/R_1\cdot 2/\varepsilon\ln R_2/R_1\cdot 9\cdot 10^2} = 60\ln\frac{R_2}{R_1}\sqrt{\frac{\mu}{\varepsilon}}\ \text{ohms.}$$

If we are concerned with two parallel round wires with a radius of R_0 which is small compared with their distance apart

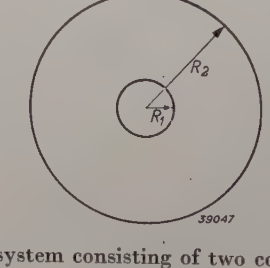


Fig. 5. Lecher system consisting of two concentric cylinders with radii R_1 and R_2.

d (*fig. 6*), the capacity and self-induction per unit of length become

$$C^I = \frac{\varepsilon}{4 \ln \dfrac{d}{R_0}} \cdot \frac{1}{9 \cdot 10^{11}} \text{ farads/cm,}$$

$$L^I = 4\mu \ln \frac{d}{R_0} \cdot 10^{-9} \text{ henrys/cm.}$$

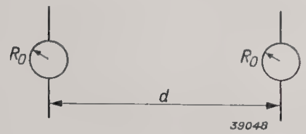


Fig. 6. Lecher system of round wires with a radius R_0 and a distance d between them.

The velocity of propagation is of course again the velocity of light divided by $\sqrt{\varepsilon\mu}$, and for the wave resistance one now finds:

$$\zeta = \sqrt{4\mu \ln \frac{d}{R_0} \cdot \frac{4}{\varepsilon} \ln \frac{d}{R_0} \cdot 9 \cdot 10^2} = 120 \ln \frac{d}{R_0} \sqrt{\frac{\mu}{\varepsilon}} \text{ ohms.}$$

In all these cases it is tacitly assumed that no energy losses occur in the self-inductions and capacities, so that the waves are propagated unweakened along the Lecher system [4]).

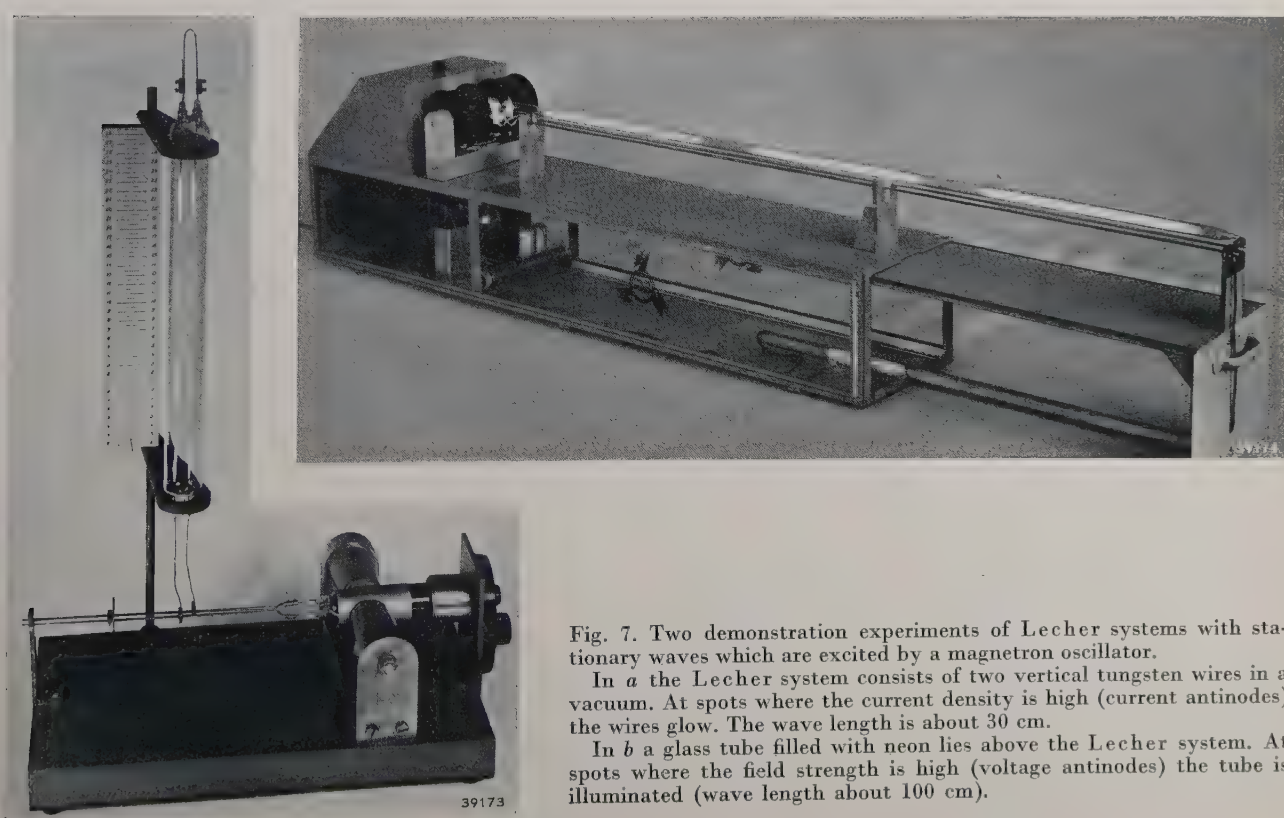
[4]) In the propagation of light and of radio waves in a vacuum no energy losses occur either, but nevertheless the amplitudes decrease in inverse proportion to the distance to the source of radiation, due to the spreading of the energy over larger and larger areas. To this corresponds the fact that upon propagation through space, instead of an expression of the form $f(t-z/v)$, an expression of the form $\dfrac{f(t-R/v)}{R}$ occurs. The parallel conductors thus keep the radiation energy better together in propagation along a Lecher system.

If the heat losses which occur in a Lecher system are taken into account, the amplitudes become smaller during the propagation along the system. Another cause for such a decrease lies in the fact that due to the finite distance between the two wires some radiation will always occur, since to a certain degree they will act as a loop aerial. We shall return later to such phenomena; for the present we shall continue to describe the behaviour of Lecher systems in so far as the resistance and the radiation loss play only a negligible part.

Stationary waves

If a Lecher system is not terminated with its own wave resistance ζ, but with an arbitrary impedance, a wave is entirely or partially reflected as already mentioned and stationary waves occur (see *fig. 7*). Before formulating this process mathematically we shall give a qualitative discussion of the phenomenon for the simple cases of a short-circuited or an open end.

In the left-hand half of *fig. 8* there is a positive and a negative charge which move on the upper and lower wires, respectively, of the Lecher system toward the short-circuited end. This end has the resistance zero, so that the charges e there pass unhindered, and will move back again with the same velocity over the lower and upper wires, respectively, of the system, as is drawn below. The



b

a

Fig. 7. Two demonstration experiments of Lecher systems with stationary waves which are excited by a magnetron oscillator.

In *a* the Lecher system consists of two vertical tungsten wires in a vacuum. At spots where the current density is high (current antinodes) the wires glow. The wave length is about 30 cm.

In *b* a glass tube filled with neon lies above the Lecher system. At spots where the field strength is high (voltage antinodes) the tube is illuminated (wave length about 100 cm).

current i and voltage V corresponding to these moving charges e are also indicated, and it is clear that at this short-circuited end the current is reflected unaltered in the same wire, while the voltage between the two wires is reflected with reversed sign. This corresponds to the fact that at the short-circuited end current can flow, but that there can be no voltage here, since the incident and reflected voltage waves always compensate each other here.

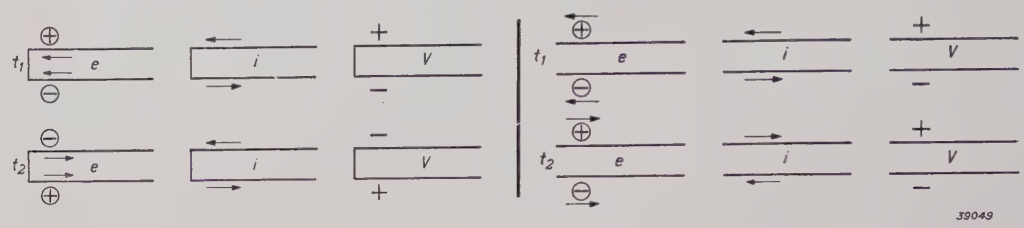


Fig. 8. Diagrammatic representation of the motion of charge e, currents i and voltage V in the neighbourhood of a short-circuited or open end, respectively, of a Lecher system.

With an open end, to which the right-hand half of fig. 8 refers, an incident charge e is reflected on the same wire, because it has nowhere else to go. The reflected current i is thus reversed in sign while the voltage V is reflected with the same sign. At an open end, therefore, there may indeed be a voltage, but no current can flow, since the incident and reflected current waves always compensate each other there.

If we now consider a Lecher system extending to an infinite length toward the left with a short-circuited end at $x = 0$ (*fig. 9*), on which as a special case a voltage wave $V_1 = \sin\omega\,(t-z/v)$ moves from left to right, a second voltage wave $V_2 = -\sin\omega\,(t-z/v)$ is there reflected toward the left, so that there is a resultant stationary wave V:

$$V = V_1 + V_2 = -2\cos\omega t\sin\omega z/v \quad . \quad . \quad (16)$$

At all points with $\omega z/2\pi\, v = z/\lambda = n/2$, where n represents a whole number, the voltage is always zero. These points are therefore voltage nodes lying at intervals of a half wave length λ. To the travelling voltage waves V_1 and V_2 according to (9) and (10) belong the travelling current waves

$$\left.\begin{aligned} i_1 &= \frac{1}{\zeta}\sin\omega\left(t-\frac{z}{v}\right), \\ i_2 &= \frac{1}{\zeta}\sin\omega\left(t+\frac{z}{v}\right). \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (17)$$

These always reinforce each other at the short-circuited end where a current antinode will occur, which may also be seen directly from the formula for the stationary current wave which occurs as a result:

$$i = \frac{2}{\zeta}\sin\omega t\cos\omega z/v \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

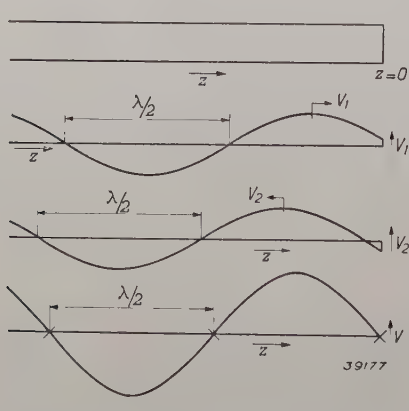


Fig. 9. Reflection of the travelling voltage wave V_1 at the short-circuited end at $z = 0$. The sum of the incident wave V_1 and reflected wave V_2 is the stationary wave V which has nodes at intervals of a whole number of half wave lengths from the short-circuited end of the Lecher system.

If we now consider (16) and (18) somewhat more closely, we see that with the short-circuited Lecher system the current i is 90° behind the voltage V at points close to the short circuit, *i.e.* with sufficiently small negative values of z, while the quotient of the amplitudes of voltage and current amounts to $\zeta\tan\omega z/v$ at any given point. The short-circuit impedance Z_k of a Lecher system with a length l is thus purely imaginary, and is given by

$$Z_k = j\zeta\tan 2\pi l/\lambda \quad . \quad . \quad . \quad . \quad . \quad (19)$$

For a length l which is small compared with the wave length λ, therefore, the short-circuit impedance becomes

$$Z_k = j\zeta 2\pi\frac{l}{\lambda} = j\sqrt{\frac{L^I}{C^I}}\,\omega l\sqrt{L^I C^I} = j\omega L^I l, \quad . \quad . \quad (20)$$

so that a small section of short-circuited Lecher system actually behaves as a self-induction with a value L^I per cm of length. According to formula (19), however, the reactance increases more rapidly than proportional to the length l for the short-circuit Lecher system, so that for a length of $\lambda/4$, for instance, we obtain an infinitely large reactance, which means that at the input of the short-circuited

Lecher system a current node occurs. Such a system can be used as an oscillator curcuit. For a Lecher system with a length between $\lambda/4$ and $\lambda/2$ the reactance is negative, so that it acts as capacity.

In practice use is commonly made of short sections of short-circuited Lecher system as self-induction. We shall give a few such examples here. In the case of radio valves for short waves the capacity is often quite large between points, between which it is desired to introduce an impedance. One then does not make the capacity of the LC circuit to be used variable, because this would mean an extra capacity and therefore a reduction in the impedance attainable. It is then better to tune with a variable self-induction, for which a short section of Lecher system with a movable short-circuiting shunt (*fig. 10*) can very well be used. *Fig. 11* shows the practical application of this device in an oscillator such as is used in the experimental short-wave link [5]) between Eindhoven and Tilburg.

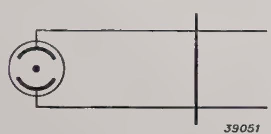


Fig. 10. A short of Lecher system which is provided with a sliding short-circuit bridge, functions as a variable self induction with which it is easily possible to tune the relatively large capacities between the electrodes of radio valves.

Fig. 11. Triode oscillator in which the admittances of the inter-electrode capacities of anode and control grid are compensated with self-inductions in the form of Lecher systems connected in parallel. With the third Lecher system, which is connected to the cathode, the back coupling is regulated.

Another example is the following. When radio valves are used at very high frequencies it often happens that reflections of the electromagnetic waves occur at the leads through glass. The capacity which is responsible for such reflections can be eliminated by connecting in parallel a Lecher system with a suitably set self-induction (*fig. 12*). A practical example of this is also given as applied in a magnetron oscillator (*fig. 13*).

Just as we have seen in the foregoing considerations that a small section of Lecher system with a short-circuited end behaves like a self-induction, it is also easy to understand that a small section of Lecher system with an open end behaves like a capacity. We here obtain as a special case of the travelling current waves which must compensate each other for $z = 0$ and the travelling voltage waves which are equal at that point:

$$\left.\begin{aligned} i_1 &= +\frac{1}{\zeta}\sin\omega(t - z/v) \\ i_2 &= -\frac{1}{\zeta}\sin\omega(t + z/v) \end{aligned}\right\} \quad . \quad . \quad . \quad (21)$$

and

$$\left.\begin{aligned} V_1 &= \sin\omega(t - z/v), \\ V_2 &= \sin\omega(t + z/v). \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (22)$$

It then follows from (21) and (22) for the stationary waves that

$$\left.\begin{aligned} i &= -\frac{2}{\zeta}\cos\omega t\sin\omega z/v, \\ V &= 2\sin\omega t\cos\omega z/v. \end{aligned}\right\} \quad . \quad . \quad (23)$$

If we compare (23) with (16) and (18) we see that with the open Lecher system the stationary waves

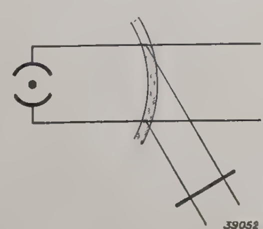


Fig. 12. Lecher system with movable short-circuit bridge for tuning the capacity due to the lead through the glass.

[5]) Philips techn. Rev. **2**, 173, 1937.

are shifted just a quarter of a wave length with respect to those with the short-circuited Lecher system.

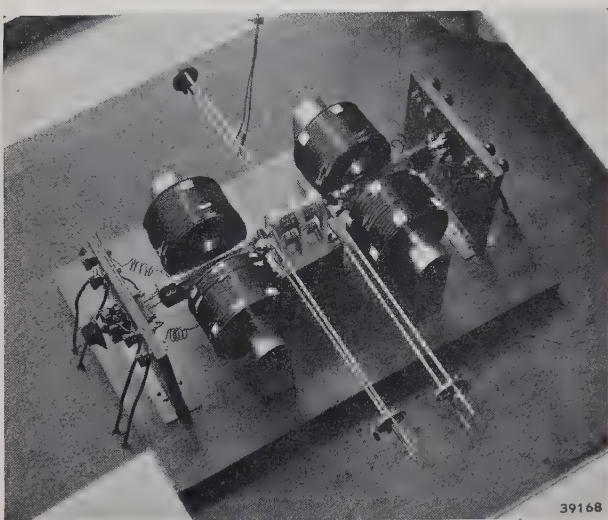


Fig. 13. Magnetron oscillator with two leads through glass, tuned by Lecher systems. The third Lecher system forms the anode impedance of the two valves.

Furthermore, it follows from (23) that with the open Lecher system at points with small negative values of z the current leads the voltage by exactly 90°, so that the open impedance Z_0 is negative imaginary and becomes equal to

$$Z_0 = -j\zeta \text{ c tan } 2\pi \frac{|z|}{\lambda}, \quad . \quad . \quad . \quad . \quad (24)$$

where $|z|$ represents the absolute value of z, *i.e.* the length l of the Lecher system. Z_0 becomes equal to zero at an uneven number of quarter wave lengths from the open end, which means that there the voltage nodes are situated. At an even number of quarter wave lengths from the open end, on the other hand, Z_0 is infinitely large, which corresponds to the current nodes. For a short section of open Lecher system the impedance Z_0 is now better written as

$$Z_0 = -\frac{j\zeta}{\tan 2\pi l/\lambda} \approx -j\sqrt{\frac{L^I}{C^I}} \frac{1}{\omega l \sqrt{L^I C^I}}, \cdot (25)$$

so that we immediately see its behaviour as capacity C^I per unit of length:

$$Z_0 = \frac{1}{j\omega C^I l} \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

If we multiply the short-circuit impedance Z_k and the open impedance Z_0 by each other, formulae (19) and (24), we obtain the following remarkable relation:

$$Z_k Z_0 = \zeta^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

which is valid for every length of the Lecher system. The wave resistance is thus always the geometric average of short-circuit and open impedance, and may therefore be determined by measuring the two as is often done in practice.

The difference in behaviour between a Lecher system terminated by its wave resistance on the one hand, and a short-circuited or open Lecher system on the other has now been thoroughly dealt with. In the first case current and voltage are everywhere in phase and the energy is propagated unchanged along the Lecher system in order finally to be converted into heat in the pure resistance which terminates the system. In the other case current and voltage are everywhere shifted 90° relatively in phase, and the energy thus oscillates continually back and forth between the electrical and the magnetic field which must alternately be built up and broken down by the stationary oscillations of voltage and current. The Lecher systems with travelling waves may be used for the transfer of electromagnetic energy, while those with stationary waves are often used at high frequencies in such places where at lower frequencies an ordinary LC circuit can be used.

Lecher system as coupling line

If we have a Lecher system closed at point *1* by any given impedance Z_1, the (travelling or stationary) electromagnetic waves at that extremity satisfy the following condition:

$$\frac{V_1}{i_1} = Z_1.$$

At a point *2* at a distance of half a wave length from *1* (*fig. 14*) all components of current and voltage are equal and opposite to those at *1* at every moment, and this means that the impedance Z_2, which can be measured at point *2* of a Lecher system which is closed by Z_1 at *1*, is simply the same as this terminating impedance Z_1.

$$Z_2 = \frac{V_2}{i_2} = \frac{-V_1}{-i_1} = Z_1.$$

In the same way of course for a Lecher system of a whole number of half wave lengths which is

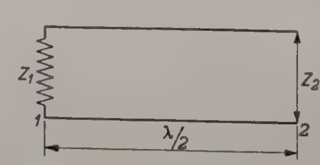


Fig. 14. A Lecher system closed at one end *1* by any given impedance Z_1 exhibits at point *2*, which lies a half wave length from *1*, an impedance $Z_2 = Z_1$.

terminated by any given impedance Z, the impedance at its input is always equal to this Z. From this we see, therefore, that a Lecher system of a of a whole number of half wave lengths is suitable for including in a given circuit the two terminals of an impedance which would otherwise be inaccessible, without the value of the impedance being apparently changed in this circuit.

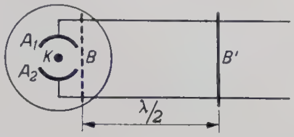


Fig. 15. If the tuning bridge B cannot be put into position because it would fall inside the valve, the same result can be obtained by means of a bridge B' a half wave length farther away.

When radio valves are used on short waves it often occurs that in order to obtain resonance in the anode circuit the bridge B should actually be introduced inside the valve. Instead of this, however, there is no objection to introducing the bridge B' half a wave length away on the supply lines, as is represented diagrammatically in *fig. 15*. This case is illustrated in fig. 7*b*. In order to make more than one half wave length visible the bridge is introduced two half wave lengths farther away than in fig. 15. *Fig. 16* represents such a connection between the control grids of a double pentode.

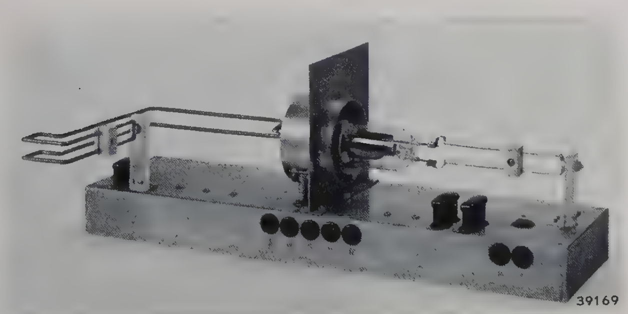


Fig. 16. Double beam tetrode of the wireless telephone connection Eindhoven-Tilburg. Between the two control grids is a tuning bridge such as is shown diagrammatically in fig. 15.

Lecher system as impedance transformer

We shall now consider Lecher systems which are a quarter wave length long and terminated at the end *1* by any given impedance Z_1. We are interested in the impedance Z_2 at the other end *2* which is separated from the closed end *1* by a distance $\lambda/4$. It is found that the product of these two impedances is equal to the square of the wave resistance:

$$Z_1 Z_2 = \zeta^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

If an impedance Z_2 is included in any given circuit by means of a Lecher system of an uneven number of quarter wave lengths, it behaves as a directly connected impedance with the value $Z_1 = \zeta^2/Z_2$. Thus in general a Lecher system of the length $(2n + 1)\ \lambda/4$ acts as an impedance transformer, and it may be used to connect two circuits of which it is desired that the loading impedance of the first shall differ from the input impedance of the second.

Such a case occurs for example when an aerial must be adapted to a supply line. If a given supply line is present, the question may be asked as to the resistance with which this must be terminated so that the losses will be as small as possible. The line should then be terminated by its own wave resistance ζ so that travelling waves will occur. The aerial to which the energy must be conducted will, however, in general have a different radiation resistance than ζ, so that it is necessary to place an impedance transformer between them. If for example the supply line has a wave resistance of 300 ohms, while the freely radiating dipole aerial of $^1/_2$ wave length has a radiation resistance of 73 ohms, a quarter wave length transformer with a wave resistance of $\sqrt{300 \times 73} \approx$ ohms should be placed between them.

The adaptation between supply line and resistance to be supplied R (aerial for instance) might also be achieved without an impedance transformer, by so changing the distance between the wires of the supply line that ζ becomes equal to R. The losses would, however, increase, since with a constant current amplitude at the end of the supply line the stationary waves pass over into travelling waves, and the average current amplitude along the supply line becomes greater. One may not therefore say that the absence of stationary waves on supply lines is desirable in all circumstances.

Resonance resistance and quality factor

We shall now take the energy losses into account in such a way that we leave the current distribution as if there were no losses.

For a short- circuited Lecher system of a quarter wave length which is used as a circuit element, we wish to know how its impedance changes with the frequency. In the article already referred to [6]) we have made use of the quality factor Q to characterize the behaviour of resonance circuits for high frequencies. This is defined as the quotient of the resonance frequency ω_0 and the resonance width $\Delta\omega$, and may in general also be considered as 2π times the quotient of field energy and heat developed

[6]) Philips techn. Rev. **6**, 217, 1941.

per period:

$$Q = \frac{\omega_0}{\Delta\omega} = 2\pi \frac{\text{field energy}}{\text{heat developed per period}} \cdot \quad (29)$$

From this it now follows for the short-circuited Lecher system of a quarter wave length that

$$Q = \frac{\omega L^I}{r^I}, \quad \cdots\cdots \quad (30)$$

when r^I represents the ohmic resistance per cm length.

The resonance resistance R is by definition equal to the quotient of the mean square of the voltage V and the heat W developed per second. In the case of a Lecher system of a quarter wave length one calculates for this

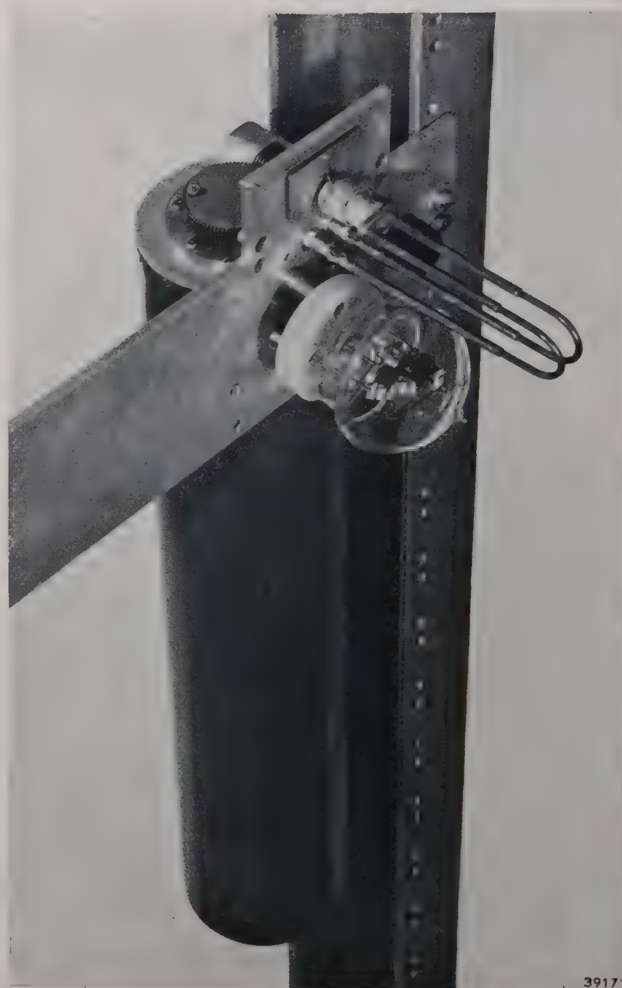
$$R = \frac{L^I}{C^I r^I \lambda/8} = \frac{4}{\pi} Q \zeta . \quad . \; . \; . \quad (31)$$

If it is desired to use a Lecher system of a quarter wave length in an amplifier circuit, the resonance resistance must be large, and at a given sharpness of resonance, *i.e.* a given ε, care must therefore be taken that the wave resistance ζ is large. In the three cases of Lecher systems already mentioned (figs. 4, 5 and 6) one finds for the resistance r^I per cm, the quality factor Q and the resonance resistance R, the formulae given in the table below, in which δ stands for the depth of pentetration of the skin effect.

	r^I	Q	R
1)	$\frac{240\pi^2\delta}{b\lambda}$	$\frac{d}{\delta}$	$\frac{480\,d^2}{b\delta}$
2)	$\frac{60\pi\delta}{\lambda}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)$	$\frac{2}{\delta}\frac{R_1 R_2}{R_1+R_2}\ln\frac{R_2}{R_1}$	$\frac{480}{\pi\delta}\frac{R_1 R_2}{R_1+R_2}\left(\ln\frac{R_2}{R_1}\right)^2$
3)	$\frac{120\,\pi\delta}{R_0\lambda}$	$\frac{2R_0}{\delta}\ln\frac{d}{R_0}$	$\frac{960}{\pi}\frac{R_0}{\delta}\left(\ln\frac{d}{R_0}\right)^2$

In general the quality factor Q is proportional to the quotient of volume and surface of the oscillation circuits. In the last case, two round parallel wires, a volume of the system cannot well be given, but this is possible in the first and second cases. Particularly in the case of the Lecher system of two parallel strips it is immediately evident that from $Q = d/\delta$ it follows that Q is equal to $2/\delta$ times the quotient of volume and surface of the oscillation circuit, which is also confirmed for two concentric conductors whose radii R_1 and R_2 do not differ too much. For two concentric cylinders whose radii are very different the current density in the inner cylinder is much greater than in the outer, and consequently this general formula no longer holds exactly. From the second line of the table it is possible to calculate those ratios of the radii of the two concentric cylinders for which the quality

a



b

Fig. 17. Concentric open Lecher system of slightly more than a quarter wave length, which serves as a practically loss-free small self-induction for the stabilization of the high-frequency oscillations excited by a radio valve. The inner rod is made of quartz to prevent thermal variations in length, and is surrounded by a covering of copper in which there is an accordionlike connecting piece. In a the components may be seen, in b the application of the system in a short-wave transmitter of 1.2 m wave length.

factor Q and the resonance resistance R are as large as possible. One finds then $R_2/R_1 = 3.7$ and approximately 9, respectively.

Lecher system as a stabilizer

The capacities between the electrodes of transmitting valves do not remain entirely constant while the valve is in use, and since these capacities form part of the tuned circuit the frequency of the oscillation excited varies. This is avoided by the use of connections in which a large capacity is connected in parallel with such variable capacities so that the influence of the latter becomes much smaller. The oscillation circuit is then further tuned to resonance by a self-induction which is in parallel with these large capacities and which must therefore be small. In addition to cavity resonators, concencentric open Lecher systems can also very well be used for this purpose. Such Lecher systems have a very high quality factor, and with a length of slightly more than a quarter wave length, they form a small, practically loss-free self-induction as may be seen directly from (24). Such a concentric Lecher system to be used as stabilizer in short-wave transmitters is shown in *fig. 17*.

Radiation losses

In the foregoing discussions we have only taken into account the ohmic losses in the Lecher system by ascribing to it a resistance r^I. Radiation losses may, however, also occur, and we shall discuss them briefly in conclusion. In practice radiation of energy is often avoided by shielding the Lecher system by means of a metal tube. If, however, this has not been done, then with a short-circuited Lecher system of a quarter wave length with a distance d between the conductors, the energy radiated per second is approximately

$$P = 1\,200\, i_0{}^2 \frac{d^2}{\lambda^2} \text{ watts}, \quad . \quad . \quad . \quad (32)$$

where i_0 is the maximum current in the bridge. The same amount of heat would be developed in an equivalent resistance r_{eq} per cm distributed uniformly along the Lecher system:

$$i_0{}^2\, r_{eq}\, \lambda/8 = 1\,200\, i_0{}^2 \frac{d^2}{\lambda^2},$$

so that

$$r_{eq} = \frac{9\,600\, d^2}{\lambda^3} \cdot \quad . \quad . \quad . \quad . \quad (33)$$

For a Lecher system of a quarter wave length which consists of round wires with a diameter of 2 mm stretched at a distance of 1 cm away from each other, the following equivalent radiation resistance is found at a wave length of for instance 75 cm:

$$r_{eq} = 0.025 \text{ ohms per cm}, \quad . \quad . \quad . \quad . \quad (34)$$

which is of the same order of magnitude as the ohmic resistance r^I per cm for this system.

MERCURY LAMPS FOR USE IN MAKING HELIOGRAPHIC PRINTS

by A. A. PADMOS and J. VOOGD.

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The requirements are studied which must be made of lamps for use in making heliographic prints. A mercury discharge lamp with atmospheric pressure constructed for this purpose is briefly described. In conclusion the best method of using this lamp in heliographic printing machines is indicated.

Introduction

With the help of the heliographic printing process it is possible to make reproductions quickly in natural size of tracings, pages of typing and the like. The method of the "contact print" is usually applied. The light passes through the "original" which is to be reproduced and then falls upon the printing paper which is placed behind it. In simple printing frames such contact prints are made one at a time as in making copies in ordinary photography. In larger printing machines the printing paper, together with the original, is carried by a transport band along the back of a bent glass surface. The operation of such a machine is represented diagramatically in *fig. 1*. A source of light L illu-

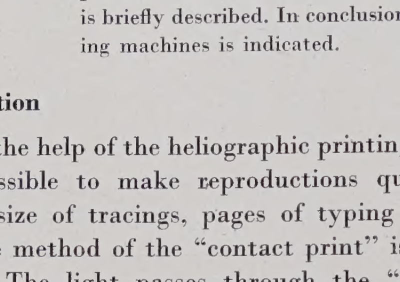

Fig. 1. Principle of the method of operation of a heliographic printing machine. L source of light, G glass plate, T transport band running over the cylindrical rollers A, B and C.

minates the cylindrically bent glass plate P. The transport band T runs along the back of this plate. At the roller A the original together with the printing paper is inserted between the glass and the transport band. The speed with which the transport band T carries the paper along the glass then determines the time of exposure. At the roller B the original and the print are taken off the machine and the print is then developed. With the help of the roller C the transport band may be put under more or less tension.

The success of this method is chiefly due to the fact that cheap kinds of printing paper can be obtained, which because of certain properties are especially suitable for use on a technical scale. One of these is the fact that with these kinds of printing paper the photochemical reaction is caused by the action of violet radiation. This radiation occurs to such a small extent only in the ordinary illumination of work rooms that no special precautions need be taken for protecting the paper from the light in order to prevent premature photochemical reactions.

For the rapid production of prints an intense violet illumination must be provided. The heliographic printing process would not have become so common if there had been no sources of radiation available whose properties are well adapted to those of the printing paper. It was only because of this that it was possible to use the short exposure times, without which the modern heliographic printing industry would be unthinkable.

Requirements for the printing lamp

Originally heliographic prints were made exclusively with daylight. The making of a single print then required an exposure time of many minutes. Practically no improvement could be obtained by using electric lamps for printing, since they also provide only very little violet radiation.

The introduction of the carbon arc lamp, however, meant an important advance, since this lamp gives a reasonable intensity of violet radiation so that with it printing speeds are reached which vary from a half to several minutes, depending on the nature of the original which is to be printed and on the kind of printing paper used.

There are, however, disadvantages connected with use of the carbon arc lamp which justify the search for a different type of light source for printing machines. For example, carbon arc lamps require much care since new carbons must be regularly inserted and the lamp glasses must be cleaned. Furthermore they often fail to burn quietly, while due to the lack of uniformity in the light distribution it is sometimes necessary to move the arc. The development of mercury vapour lamps made it possible to avoid all these difficulties. These lamps require no upkeep, burn very regularly and can be so constructed that they give a suitable light distribution.

If we briefly examine the requirements which are made of a printing lamp, the first will be that of a

short exposure time. This means that lamps must be used which have a high power and which moreover give a large part of their radiation in the violet. As to the total output of the lamps in a printing machine, it will be limited by the maximum temperature which is permissible on the glass plate and transport band. In large printing machines with carbon arcs the lamps consume 6 to 10 kW. The total power of the mercury vapour lamps which must be installed in such a machine may therefore not be greater than this order of magnitude.

In the second place the efficiency and the life of the mercury vapour lamps should justify their use as printing lamps economically also, while in the third place the dimensions of the lamp should be chosen so that a uniform light distribution is obtained. The linear form of the mercury discharge lamp is particularly suitable for this purpose. For a printing machine with a transport band 1 m wide a satisfactorily uniform light distribution can be obtained with two lamps 50 cm long in a line.

Finally it is necessary that the current or voltage should not be unreasonably high upon ignition or during use. It has indeed been found possible to construct a mercury vapour lamp which satisfies the requirements here mentioned and which has already proved its value as a printing lamp in practical use.

Construction of the printing lamp

In the development of the printing lamp the foundation was a mercury discharge lamp with a pressure of about 1 atmosphere. Since during use the temperature of the surroundings and the cooling of the lamp are practically constant a single layer glass wall was sufficient. The distance between the oxy-cathodes is 55 cm, while the external diameter of the lamp is 3 cm. The length of the light column of 55 cm was chosen in order to be able to illuminate a width of 100 to 110 cm uniformly with two lamps placed end to end or overlapping slightly. The lamp consumes a power of 1 900 W at a current of 8.7 A and a working voltage of about 240 V. In series with a suitable choking coil the lamp can be connected to an A.C. voltage of 380 V. With the help of a specially constructed leakage transformer the lamp can also be connected to 220 V. Lamp and series apparatus consume a total of about 2 kW. In *fig. 2* this printing lamp with choking coil is shown.

In order to characterize the spectral energy distribution of the lamp, the energy current density I_λ in erg/cm^2 sec in the perpendicular plane bisecting the axis of the lamp at 100 cm distance from the axis for different wave lengths is given in *table I*. In the last column of table I the contribution of the different wave lengths to the photochemical reaction in the printing paper is given. For this purpose I_λ is multiplied by the spectral sensitivity V_λ of the paper and by the spectral transmission d_λ of the glass plate. The values in the table are given on a relative scale such that for the wave length 4 047 Å the value of 100 is obtained.

The speed at which prints can be made with this mercury lamp is practically the same as with an arc lamp of the same power. The exposure times necessary for making a print vary between about 10 and 15 sec.

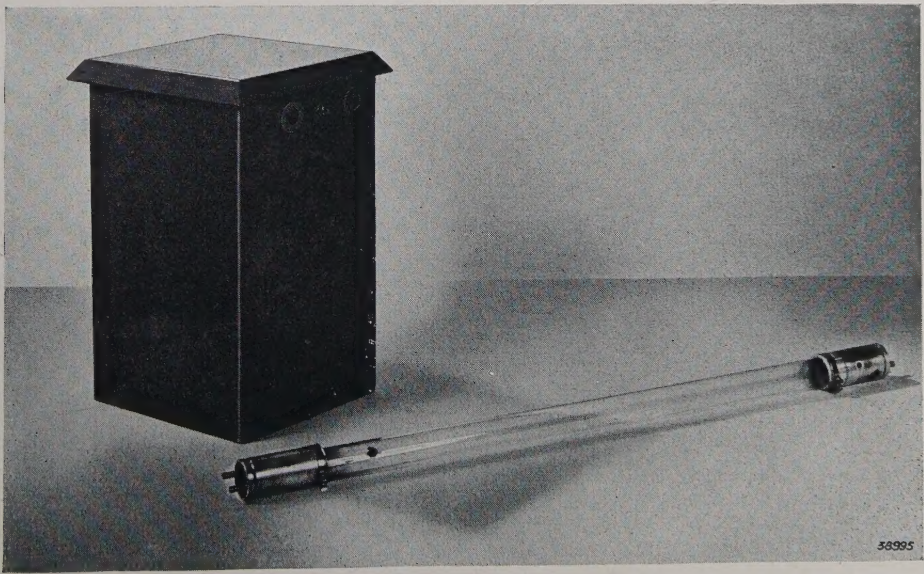

Fig. 2. Printing lamp with an arc length of 55 cm with corresponding choking coil.

Table I

λ in Å	I_λ in erg/cm^2 sec at a distance of 100 cm	$I_\lambda\ V_\lambda\ d\lambda$ in a relative scale
5 770-5 791	7 920	0
5 461	6 360	0
4 358	4 930	132
4 047	2 520	100
3 655	3 490	75
3 342	70	0.20
3 130	105	0
3 012	20	0

Use of the printing lamp

The mercury lamps here described have of course quite a different light distribution from that of the carbon arc lamps used formerly. In the end the use of the new printing lamps will also lead to a different construction of the printing machine, but it has, nevertheless, been found quite possible to replace the carbon arcs in existing machines by mercury lamps.

Fig. 3 shows such a printing machine which is now equipped with mercury lamps. By placing mirrors at the ends of the lamps perpendicular to the axis of the tube the distribution of the illumination could be made more uniform and, moreover, the necessary exposure time could be shortened. In practice, however, it is found that the refitted printing machine of fig. 3 is quite satisfactory; the advantages of the mercury discharge over the carbon arc are fully exploited, while with the same power of the lamps prints can be made at the same speed.

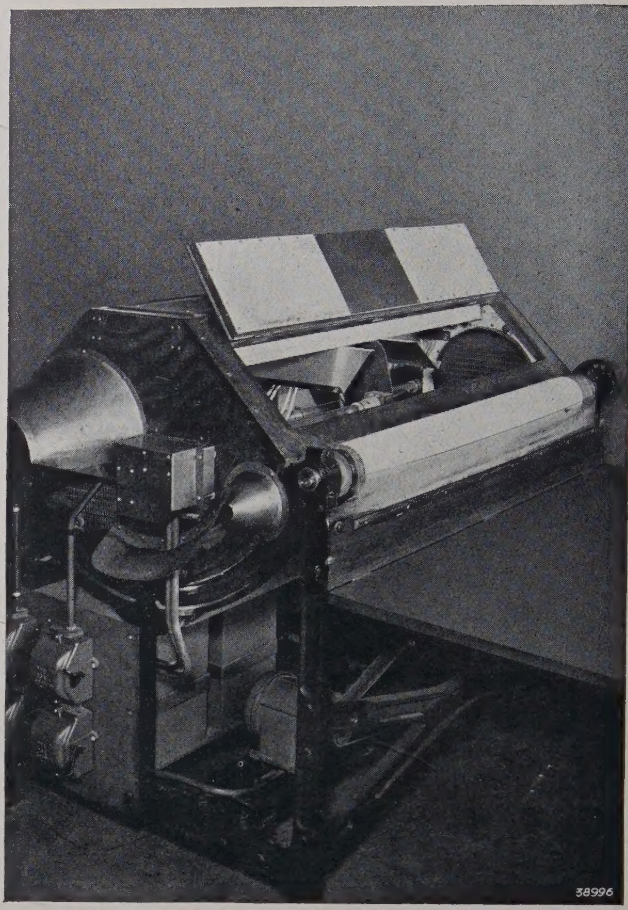

Fig. 3. Printing machine in which the carbon arcs have been replaced by mercury lamps. To the left below the machine may be seen the choking coils belonging to the mercury lamps.